TECHNICAL REPORT NO. 2-48

RESPONSE OF FIBROUS-REINFORCED CONCRETE TO EXPLOSIVE LOADING

Prepared by

G. R. WILLIAMSON

JANUARY 1966

DEPARTMENT OF THE ARMY

OHIO RIVER DIVISION LABORATORIES, CORPS OF ENGINEERS

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SUMMARY

The results of 72 explosive loading tests on fibrous-reinforced concrete slabs are presented. The slabs, 32x32x4 inches, were tested in a vertical position with 4 inches of bearing on the two vertical sides. A 10-pound cylindrical charge of Composition B high explosive was used as the loading mechanism. Various synthetic and steel fibres were used as random reinforcing to develop a concrete that would resist explosive loadings. Evaluation was based upon the ability of the fibrous concrete to reduce the amount and velocity of fragments produced by the explosive loading. The values obtained from tests of plain, unreinforced concrete slabs were used as the basis of comparison. It is shown that when plain concrete slabs are reinforced conventionally to resist the shear and flexural stresses, there is no reduction in fragment velocities or fragmentation; and, that similarly reinforced slabs of fibrous concrete show 20% reduction in velocities, and over 80% in fragmentation.

A study made to determine the value of high-strength and medium-strength concrete, when used in conjunction with fibres, revealed no significant difference in response under the explosive loading.

The mode of failure for a slab supported on two sides only is shown to be primarily flexural.

Detailed descriptions of each individual test are presented, together with conclusions and recommendations for future work.

PREFACE

The investigation reported herein was authorized by the Office, Chief of Engineers (ENGEC-BE), Department of the Army, by letter dated 19 November 1964, subject: "Naval Ordnance Test Station, MIPR 60530/3010-1532-65". Funds were provided by the Dividing Wall Working Group of the Armed Services Explosives Safety Board. This investigation is part of an overall program to develop materials for use in structures where explosives are manufactured or stored.

The work was performed by the Ohio River Division Laboratories, U. S. Army Engineer Division, Ohio River. Personnel actively engaged with the planning, testing, analysis, and reporting of this project were Messrs. F. M. Mellinger, I. Narrow, R. L. Hutchinson, W. W. Roberts, D. Birkimer, and G. R. Williamson. This report was prepared by Mr. G. R. Williamson.

The Director of the Ohio River Division Laboratories during this investigation was Mr. Frank M. Mellinger; the Assistant Director was Mr. John M. Merzweiler.

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RESPONSE OF FIBROUS-REINFORCED CONCRETE TO EXPLOSIVE LOADINGS

PART I: INTRODUCTION

Background

1. The term "dividing wall" is a name given to represent any partition placed between weapons in explosive storage facilities. Its primary function is to prevent chain reaction in case of the detonation of any stored item. The procedure used to design a reinforced concrete dividing wall follows the standards and regulations of the Ordnance Safety Manual. At present, there is no precise method of analysis with which to determine the degree of protection afforded by walls designed in accordance with these specifications. As a result, full-scale tests have shown that previous estimates of explosive storage limits are, in many cases, incorrect. This has resulted in a decrease in the amount of explosives permitted to be stored in some of the existing facilities, and thus an increase in the overall cost of storage.

2. Recognizing the need for more precise methods of designing structures that may be subjected to close-in blasts, a broad program, under the direction of Picatinny Arsenal, was initiated, in which one of the objectives was the establishment of structural design criteria for protective walls in explosive manufacturing and storage systems. The results of this program are contained in the publication "Industrial Engineering Study to Establish Safety Design Criteria for Use in Engineering of Explosive Facilities and Operations"[1]*. A method of design has been developed to account for the close-in effects of the explosion. This method is based on theoretical considerations only; however, confirmatory tests are now in progress.

3. A program to investigate wall response is presently being conducted at the China Lake Naval Ordnance Test Station, under the direction of Picatinny Arsenal. One phase of this program includes the testing of reinforced concrete, structural steel, and composite slabs at one-third scale[2].

4. Since FY 1963, the Ohio River Division Laboratories has been conducting an investigation to develop shock-resistant concrete by the inclusion of

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* Raised numerals in parenthesis refer to references.

random fibrous-reinforcement[3]. Impact tests on small fibrous-reinforced concrete cylinders[4], and high-explosive tests of fibrous-reinforced concrete slabs have shown this material to be more effective than plain concrete in resisting shock loading. Static flexural tests of fibre-reinforced concrete beams showed that the addition of fibres to the concrete enabled the beams to continue to carry loads, after the initial crack occurred. The fibrous materials which produced the best results were either short lengths of nylon fibres or small diameter steel wires.

Objective of Investigation

5. The primary objective of this investigation was to determine the optimum mix design of fibrous-reinforced concrete that would limit fragmentation or spalling of concrete, and reduce the velocity of the fragments to an acceptable level, when the concrete was subjected to explosive blast loadings.

Scope

6. The following procedures and tests were used to accomplish the objective of this investigation:

a. High explosive tests of fibrous reinforced concrete slabs, 32x32x4 inches, to determine the effectiveness of various materials in reducing the amount and velocity of fragments from the slab.

b. Static flexural and compressive tests for maintaining quality control of the concrete.

7. The investigation was conducted in three phases as follows. Phase I was used to develop testing techniques, and to provide preliminary data on the effectiveness of various fibrous materials. Phase II consisted of more detailed tests of the most effective fibres as determined in Phase I, and the evaluation of shock-absorbing materials when used in conjunction with these fibres. In Phase III, slabs were tested at various scaled distances to determine the optimum distance at which no fragmenting would occur for both plain and fibrous-reinforced concrete. In addition, the effectiveness of fibres when used in conjunction with conventional reinforcing bars was investigated.

8. This report presents a description of the fibrous materials and concrete mixes used to fabricate the test slabs, the test procedures and results of the tests, and conclusions and recommendations for future work.

PART II: MATERIALS AND CONCRETE MIXES

9. The fibrous materials used as reinforcement in the concrete test slabs were nylon, polypropylene, polyethylene, chrysotile asbestos fibre, steel wire, and galvanized wire. Brief descriptions of each material used are contained below:

a. Nylon:

15 Denier x 3/4-inch long multifilament, and
.010-inch x 3-inch long monofilament.

b. Polypropylene:

.0075-inch x 1-inch long, monofilament (white), and
.0065-inch x 1-inch long, monofilament (black).

c. Polyethylene:

.011-inch x 1-inch long, monofilament.

d. Polypropylene Fly Screen:

Clear opening .068-inch each way, 12 fibres per inch, fibre diameter .014-inch.

e. Chrysotile Asbestos Fibre KB-483-4T:

All passing a 1/4-inch screen.

f. Steel Wires:

.010-inch x 1-inch long
.017-inch x 1 1/2-inch long
.032-inch x 3-inch long

g. Galvanized Wire Fly Screen:

Clear opening .058-inch x .044-inch, wire diameter .011-inch, wires per inch - 14x18.

10. The shock absorbing materials evaluated were:

a. Polyurethane Foam, 2-inch thick, 4.5 lbs/ft^3.

b. Aluminum Honeycomb, 2-inch thick, 8.1 lbs/ft^3, cell size - 3/16-inch, foil gage - .0030-inch.

11. The reinforcing used was as follows:

a. 4x4 - 8/8 wire mesh (ASTM A185)

b. No. 3 deformed steel reinforcing bars (ASTM A15 & A305)

c. 1/4-inch deformed fiberglas-polyester resin reinforcing bars.

12. Two basic concrete mixes were used for the test slabs and were as follows:

Mix A - 1 part cement to 3.29 parts aggregate, by weight; water-cement ratio, 0.48 by weight; air content, 6 - 8%

Mix B - 1 part cement to 5.43 parts aggregate, by weight; water-cement ratio, 0.61 by weight; air content, 6 - 8%

High-early-strength portland cement (Type III) and 3/8-inch maximum size aggregate were used for both mixes. One slab was made using a modified epoxy resin in place of the cement. The quantity of resin used was 10% of the weight of the aggregate.

Aggregate Gradation

Sieve	Percent Retained
3/8 inch	0
No. 4	35
No. 8	8
No. 16	14
No. 30	17
No. 50	15
No. 100	7
Pan	4
Fineness Modulus	3.94

13. All proportioning of the fibres was by volume; the amount is expressed as a percentage of the sand, cement, water, and entrained air. The coarse aggregate is neglected in the computations; the reasoning being that the fibres reinforce only the matrix. The mixing was done in a 9-cu. ft. tilting mixer. Batch sizes were large enough to make one 32x32x4-inch slab, one 6x6x3-inch beam, and three 6x12-inch cylinders for concrete control. The control specimens were tested the same day that the slabs were tested. After the slabs and control specimens were made, they were immediately placed in a 72° F moist room. On the following day, they were removed from the moist room long enough for the forms to be stripped; they were returned to moist cure until tested. A minimum of 8 days curing time was specified for the slabs. Various colors were used in the concrete to aid in the identification of the fragments.

PART III: DESCRIPTION OF TESTS

Field Tests

14. All field tests, conducted to compare fibrous-reinforced concrete with plain concrete and conventional steel bar- or mesh-reinforced concrete, were performed using 32x32x4-inch slabs, and a bare 10-pound cylindrical charge of Composition B high explosive. This size slab, at one-third scale, represents a full-scale wall 8x8x1-foot using a linear scaling relation. The 10-pound charge of high explosive, at one-third scale, represents a full-scale charge of 273 pounds, using the following scaling relation:

$$w^{1/3} = 1/3W^{1/3} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where

w = weight, in pounds, of the one-third scale charge.

W = weight, in pounds, of the full-scale charge.

The 10-pound cylindrical charge (4 3/8 x 11 1/8 inches) was located at a distance, r, from the face of the slab to produce a Z factor equal to 0.5 using the following relation:

$$Z = \frac{r}{w^{1/3}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where

r = distance, in feet, from the center of the charge to the face of the slab.

w = weight, in pounds, of the charge

The 0.5 factor is the same as for the full-scale condition; keeping this same factor for the one-third scale, results in equal pressures from the explosion on the scaled and full-scale slabs.

15. For the evaluation of the effects of shock-absorbing materials, explosive tests using the 10-pound high explosive charge with an 0.5 Z-factor were performed on slabs composed of 2 inches of reinforced concrete on each side of a 2-inch thickness of the shock-absorbing material (see Figure 3). Some tests were also performed to determine the required Z-factor that would result in no fragmentation of the concrete from the 10-pound high explosive charge. The 32x32 4-inch slabs with various types of reinforcement were used, and the charges placed at distances required for Z-factors of 0.5, 0.75, 1.00, 1.50, and 2.00.

Test Slab Construction

16. Each test slab was fabricated individually. When wire-mesh reinforcing was used, the mesh was 3/4-inch clear distance from each face. In slabs where reinforcing bars were used, the bars were placed 7/16-inch clear distance from each. The slabs were cast in metal forms, and the concrete was consolidated with a laboratory vibrator. Drawings of typical slabs are shown in Figures 1, 2, and 3.

Field Procedures

17. The slabs were tested in a vertical position with 4 inches of bearing on the two vertical sides. The cylinder of Composition B, 4 3/8-inch diameter x 11 1/8 inches long, was placed horizontally so that its center coincided with the center of the slab; and was the prescribed distance from the face of the slab. For the Phase I tests, the slabs were set on wood blocks 2x2x4 inches for testing, and there was no provision made to overcome the irregularities of the bearing surfaces. This was not satisfactory, as it allowed gases from the explosion to obscure the fragments from the camera. In subsequent tests, the bottom and the two vertical bearing surfaces were "buttered" with 1/4-inch of gypsum cement. The slab was then positioned in the test stand and the cement allowed to harden. This not only provided a uniform bearing surface, but it also prevented the gases from interfering with the photography. Five to eight tests constituted one day's test program. A steel grid was placed parallel to and 6 feet from the line of flight of the fragments as a reference base for computing the velocity of the fragments. The cameras were placed 110 feet from the slab and at right angles to the grid. Plate 1a shows the test setup; Plate 1b shows a slab in position for testing. The charge was detonated with an Engineer's Special blasting cap placed in a hole drilled in one end. The detonation was triggered by one of the cameras after it had reached a speed of approximately 2100 frames/second. When the test was completed, the fragments were gathered and pieced together for analysis. In Phases II and III,

the larger pieces were weighed, so that a comparison could be made with the unreinforced slabs as to the amount of fragments produced by each. Fragments 20 pounds or heavier were considered to be intact; and the total weight of intact pieces is presented as a percentage of the original weight of the slab. This type of an evaluation is based, in part, on the judgment of the investigator; therefore, it is of questionable value; however, it does serve to compare the value of the various fibres in reducing fragmentation.

Laboratory Tests

18. Quality-control of the concrete was maintained through compression and flexural tests. Three 6x12-inch cylinders and one 6x6x36-inch beam were made for each slab, in accordance with Corps of Engineers Method CRD-C-10-61. These specimens were tested on approximately the same day as the slab for which they were made. The testing of the cylinders followed Corps of Engineers Method CRD-C-14-63 (ASTM Designation: C39-61); the beams were tested in accordance with Corps of Engineers Method CRD-C-16-63 (in part, ASTM Designation: C78-59), using third point loading over an 18-inch span. Two tests were made on each beam. All of the control specimens contained the same fibres as the slab they represented.

19. Bond tests were conducted on the three different diameter wires and on the .010-inch nylon used in the slab tests. In addition, bond tests were run on individual polypropylene fibres extracted from the fly screen (see Plate 30). Specimens were prepared by imbedding the material to be tested one inch in concrete similar to that used in the slabs. The specimens were cured in water for 7 days, and then tested with an Instrom Universal Testing Machine. Rate of strain was 0.2 inches per minute. Results of the bond tests are shown in Table 1. The remaining fibres were not tested, since no samples suitable for bond testing were available.

PART IV: TEST RESULTS

Phase I Testing

20. Twenty-four slabs were tested as part of the Phase I program. This series of tests was intended primarily to develop testing and analysis techniques, and to determine the effectiveness of the various fibres. These results were then used to plan Phases II and III. Slabs containing mesh were fabricated with a layer of 4x4 - 8/8 wire mesh on each face, except for Test 15, where the slab contained one layer of 2x2 - 14/14 mesh at the center. Ten-pound-charges of Composition B explosive at 13 inches from the face of the slabs were used in all of the tests except No. 15, which was tested with a 2.5-pound charge of Composition C-4, spaced 5.5 inches from the face of the slab.

21. A description of each slab and the results of the tests are given in Table 2. No fragment velocity measurements were obtained for eight tests, due to a camera malfunction. The determination of the most effective fibres was accomplished by comparing the fragment velocities and the amount of breakup of the fibrous-reinforced slabs with that of the plain slabs. The maximum fragment velocity for the plain slabs averaged 233 fps; for slabs made with the .010-inch nylon and the 15-Denier nylon, the velocities averaged 190 and 188 fps respectively; for slabs made with the .032-, .017-, and .010-inch wire, the velocities averaged 189, 171, and 172 fps respectively. The amount of breakup was least for the .010-inch nylon and the .017-inch wire. Based upon these results and upon the ease of mixing of the fibres, it was decided that subsequent testing would be done with the .010-inch nylon, 15-Denier nylon, and the .017-inch wire. Since this series of tests was used primarily to develop techniques, the results are not discussed in detail.

Phase II Testing

22. Thirty-two slabs were tested as part of Phase II. The basic fibrous-concrete mixes consisted of either 2 1/2% of .010 x 3-inch nylon, 1 3/4% of 15-Denier x 3/4-inch nylon, or 2 1/2% of .017 x 1 1/2-inch steel wire. These are the materials which were judged superior in overall performance, based upon the Phase I tests. The amount of fibres used in the .010-inch nylon mixes and the .017-inch wire mixes was increased from 1 3/4% to 2 1/2%, which appeared to be the maximum amount of these fibres that could be incorporated on a large scale.

23. Test data are presented in Table 3, and are reviewed in the following

paragraphs. For convenience in making comparison, tests of slabs with similar reinforcement and similar test conditions have been grouped together. The values for the compressive and flexural strengths, maximum fragment velocity, and fragmentation, that are listed, are the averages of the several tests if more than one test was made. The distance given for the fragment scatter is that for the test that was a maximum. This distance was measured by pacing from the nearest 100-foot marker.

Tests of Plain Concrete Slabs

24. Tests 37 and 46 (See Plate 2):

Reinforcing	None
Concrete	Mix A; Z = 0.50
Average Compressive Strength, psi	6820
Average Flexural Strength, psi	860
Maximum Fragment Velocity (Avg.), fps	240
Average Fragmentation, % Intact	0.10

The slabs disintegrated completely into small rubble. Fragments were scattered to a distance of 370 feet.

25. Tests 33 and 34 (See Plate 3):

Reinforcing	4x4 - 8/8 wire mesh, each face
Concrete	Mix B; Z = 0.50
Average Compressive Strength, psi	3715
Average Flexural Strength, psi	625
Maximum Fragment Velocity (Avg.), fps	245
Average Fragmentation, % Intact	0.0

As with the slabs of Mix A, these slabs also disintegrated into small rubble. Fragments were scattered to a distance of 350 feet.

26. Discussion: There appeared to be little difference in response between the Mix A and Mix B slabs, even though there was a large difference in compressive strength (3105 psi), and the Mix B slabs contained wire mesh. All of the slabs were reduced to rubble, although the slabs with mesh produced slightly larger fragments. The maximum fragment velocities were approximately equal, as was the distance the fragments were scattered.

Test of Nylon-Reinforced Slabs

27. Tests 25, 32, and 39 (See Plates 4 and 6a):

Reinforcing. . . .	2 1/2% of .010x3-inch nylon monofilament, and 4x4 - 8/8 wire mesh on each face.
Concrete	Mix A; Z = 0.50
Average Compressive Strength, psi	5755
Average Flexural Strength, psi	840
Maximum Fragment Velocity (Avg.), fps	218
Average Fragmentation, % Intact	55

Failure was primarily by flexure, with considerable breakup of the center portion of the slabs. There was some spalling of "sheets" of concrete 1-inch thick from the wire mesh on the acceptor side of the slabs (See Plate 5). Fragments were scattered to a distance of 345 feet.

28. Tests 30 and 40 (See Plate 6b and 7a):

Reinforcing. . . .	2 1/2% of .010x3-inch nylon monofilament, and 4x4 - 8/8 wire mesh on each face.
Concrete	Mix B; Z = 0.50
Average Compressive Strength, psi	3735
Average Flexural Strength, psi	674
Maximum Fragment Velocity (Avg.), fps	240
Average Fragmentation, % Intact	63

Failure was similar to the Mix A nylon-reinforced slabs described in paragraph 27. Fragments were scattered to a distance of 295 feet.

29. Discussion: All of the nylon-reinforced slabs showed considerable shock resistant characteristics. The number of the fragments was reduced to a great extent over those from plain slabs, although the velocity was reduced only 9% for the slabs with Mix A, and none for the slabs with Mix B. There was no appreciable difference in the response of the slabs made with Mix A and Mix B, despite the large difference (2020 psi) in compressive strength.

Tests of Wire-Reinforced Slabs

30. Tests 26, 31, and 41 (See Plates 7b and 8):

Reinforcing. . . .	2 1/2% of .017 x 1 1/2-inch steel wire, and 4x4 - 8/8 wire mesh on each face.
Concrete	Mix A; Z = 0.50

Average Compressive Strength, psi	8345
Average Flexural Strength, psi	1240
Maximum Fragment Velocity (Avg.), fps	202
Average Fragmentation, % Intact	74

Failure was by shear at the supports, with breakup of the center portion of the slabs into several large pieces. Fragments were scattered to a distance of 360 feet. The average maximum fragment velocity of 202 fps was made up of velocities of 177, 190, and 240 fps from Tests 26, 31, and 41, respectively. Based upon these and the Phase I tests, it appears that the velocity from Test 41 is not consistent with the other results. The high compressive and flexural strength of the control specimens is due to the presence of the wire fibres.

31. Tests 38 and 45 (See Plate 9):

Reinforcing . . .	2 1/2% of .017 x 1 1/2-inch steel wire, and 4x4 - 8/8 wire mesh on each face.
Concrete	Mix B; Z = 0.50
Average Compressive Strength, psi	5990
Average Flexural Strength, psi	939
Maximum Fragment Velocity (Avg.), fps	217
Average Fragmentation, % Intact	72

Failure was similar to the Mix A wire-reinforced slabs. As with the above described .017-inch wire-reinforced slabs, there was no consistency in the fragment velocities. Test 38 had a maximum fragment velocity of 247 fps, while Test 45 had a maximum fragment velocity of 188 fps. Both Test 38, and Test 41, discussed in paragraph 30, deviated so greatly from the arithmetic mean that the values are suspect.

32. Test 52 (See Plate 10):

Reinforcing . . .	7 layers at 1/2 inch, of galvanized steel fly screen, and 4x4 - 8/8 wire mesh on each face.
Concrete	Mix A; Z = 0.50
Compressive Strength, psi	6570
Flexural Strength, psi	770
Maximum Fragment Velocity, fps	219
Fragmentation, % Intact	0.0

Failure was by shear at the supports, with complete breakup of the center portion of the slab. There was separation of the concrete at the layers of screen in addition to bond failure of the wire mesh. Fragments were scattered to a distance of 280 feet.

33. Discussion: The slabs reinforced with the .017-inch wire produced

fragments with the lowest velocity and maintained the highest degree of intactness. These slabs also had the widest range of velocities, 177 to 247 fps. For analysis purposes, the velocities for all of this type slab, for Phase I and II respectively, were 180 and 162 fps; 190, 177, 188, 247, and 240 fps. The arithmetic mean is 196; the standard deviation is $\pm$ 30; and the coefficient of variation is 15%. The range for plus and minus one deviation becomes 166 to 226. This effectively encompasses all of the values, except those for Tests 38 and 41, which were 247 and 240 fps respectively, or a variation of 22 and 26 percent from the mean. It is believed that this is sufficient cause for deleting these values from the final analysis. When this is done, the average maximum fragment velocity becomes 185 fps, or 77 percent of the velocity for the plain slabs. No explanation of the anomalies is offered, but it is of interest to note that both tests were performed on the same day. The response of the slab made with fly screen was poor, both in regard to the maximum fragment velocity and the number of fragments produced. The clear opening dimension was not large enough to permit the concrete to penetrate the screen; thus, the bond was not sufficient to develop the ultimate tensile strength of the wire. In addition, placement of reinforcing of this type does not appear to be practical.

Tests of Fiberglas-Reinforced Slabs

34. Test 43 (See Plate 11a):

Reinforcing	2% of .017 x 1 1/2-inch steel wire, and 1/4-inch deformed fiberglas polyester resin reinforcing bars, 4 inches on center, each way, each face.
Concrete	Mix A; Z = 0.50
Compressive Strength, psi	6900
Flexural Strength, psi	---
Maximum Fragment Velocity, fps	190
Fragmentation, % Intact	55

Failure was by shear at the supports, with complete breakup of the center portion of the slab. The bond between the concrete and the rods was insufficient to develop the full strength of the rock. The major portion of the rods remained intact during the breakup of the slab. Fragments were scattered to a distance of 335 feet.

35. Test 42 (See Plate 11b):

Reinforcing	1 3/4% of 15-Denier x 3/4-inch nylon multifilament, and 1/4-inch deformed fiberglas-polyester resin reinforcing bars, 4 inches on center, each way, each face.
Concrete	Mix A; Z = 0.50

Compressive Strength, psi	6035
Flexural Strength, psi	921
Maximum Fragment Velocity, fps	215
Fragmentation, % Intact	32

Failure was similar to that described for Test 43. Fragments were scattered to a distance of 415 feet.

36. Discussion: The maximum fragment velocities for these two slabs were reduced to 79 and 90% of the plain slabs, for the wire- and the nylon-reinforced slabs respectively. It is believed that this was due to the presence of random-reinforcing rather than to the use of the fiberglas rods, since these values are similar to those obtained for the .017-inch wire and .010-inch nylon reinforced slabs that did not contain fiberglas rods. Despite the fact that the rods were deformed, the bond with the concrete was extremely low. This is evidenced by the large number of rods that remained intact after the blast, and by the large number of fragments produced by the slabs. In addition, there was no indication that the fiberglas-reinforcing mats acted as a unit. Until some method is found to develop a greater bond between the fiberglas rods and the concrete, this material will be of little value in producing shock-resistant concrete.

Test of Polypropylene and Polyethylene Reinforced Slabs

37. Test 55 (See Plate 12a):

Reinforcing	Five layers of polypropylene fly screen at 3/4 inch, 1% of 15 Denier x 3/4-inch nylon, and 4x4 - 8/8 wire mesh on each face.
Concrete	Mix A; Z = 0.50
Compressive Strength, psi	6260
Flexural Strength, psi	885
Maximum Fragment Velocity, fps	202
Fragmentation, % Intact	56

Failure was by shear at the supports and by flexure, with considerable breakup of the center portion of the slab. There was some tendency for the concrete to separate from the screen, indicating that the bond between the screen and the concrete was low. Fragments were scattered to a distance of 276 feet.

38. Test 56 (See Plate 12b):

Reinforcing	Five layers of polypropylene fly screen at 3/4 inch, and 4x4 - 8/8 wire mesh on each face.
Concrete	Mix A; Z = 0.50

Compressive Strength, psi	6010
Flexural Strength, psi	805
Maximum Fragment Velocity, fps	177
Fragmentation, % Intact	27

Failure was by shear at the supports, with the center portion reduced to rubble. There was some separation of the concrete from the screen. Fragments were scattered to a distance of 415 feet.

39. Test 27 (See Plate 13a):

Reinforcing . . . . 2 1/2% of .0075 x 1-inch white polypropylene, and 4x4 -8/8 wire mesh on each face.

Concrete	Mix A; Z = 0.50
Compressive Strength, psi	5215
Flexural Strength, psi	865
Maximum Fragment Velocity, fps	235
Fragmentation, % Intact	65

Failure was by flexure at the center, and partially by shear at the supports. The wire mesh failed in tension. Fragments were scattered to a distance of 390 feet.

40. Test 28 (See Plate 13b):

Reinforcing . . . . 2 1/2% of .0065 x 1-inch black polypropylene, and 4x4 - 8/8 wire mesh on each face.

Concrete	Mix A; Z = 0.50
Compressive Strength, psi	5360
Flexural Strength, psi	780
Maximum Fragment Velocity, fps	211
Fragmentation, % Intact	60

Failure was by flexure at the center, and shear at the supports. The wire mesh failed in both tension and bond. The fibres appeared to be affected by the flame from the blast; and were the only fibres affected in this manner. Fragments were scattered to a distance of 330 feet.

41. Test 29 (See Plate 14):

Reinforcing . . . . 2 1/2% of .011 x 1-inch polyethylene, and 4x4 - 8/8 wire mesh on each face.

Concrete	Mix A; Z = 0.50
Compressive Strength, psi	5315
Flexural Strength, psi	755

Maximum Fragment Velocity, fps	222
Fragmentation, % Intact	44

Failure was primarily by shear at the supports, with some breakup of the middle portion of the slab. Although there was some failure of the mesh in tension, the major portion failed in bond. Fragments were scattered to a distance of 340 feet.

42. Discussion: The maximum fragment velocity of the slab made with polypropylene fly screen was only 74% of that for plain slabs, and was one of the lowest values for any of the slabs tested in Phase II. The slab that contained 15-Denier nylon in addition to the fly screen produced a maximum fragment velocity of 202 fps, or 84% of that for plain slabs. The effectiveness of the nylon is shown by comparing the number of fragments produced by the two slabs (See Plate 12). The slab without nylon was reduced to rubble, while a major portion of the slab with the nylon was contained in five large pieces. The bond between the screen and the concrete, although low, was considerably better than that for the metal screen; probably because the openings were larger. Although this material has shown some effectiveness in reducing fragment velocities, the amount of gain hardly overcomes the impracticality of placing the fibres in layers of screen. The slabs that contained the randomly distributed fibres responded in a manner identical to the nylon-reinforced slabs. The average fragment velocity was 223 fps, as compared to 218 fps for the nylon. The slabs broke into five or six large pieces, and showed considerable resistance to shock loading. The black polypropylene appeared to melt in the presence of the blast flame, and was the only fibre that was affected in this manner.

Test of Slab Made with Epoxy Concrete

43. Test 36 (See Plate 15a):

Reinforcing	1% of .010-inch steel wire, and 4x4 - 8/8 wire mesh on each face.
Concrete	Z = 0.50
Compressive Strength, psi	2680
Flexural Strength, psi	990
Maximum Fragment Velocity, fps	247
Fragmentation, % Intact	20

Failure was by shear at the supports, with complete breakup of the center portion of the slab. The material separated from the mesh, leaving it fairly intact. Fragments were scattered to a distance of 365 feet.

44. Discussion: Close examination of the failed slab showed that there was insufficient bond between the epoxy and the aggregate, and between the matrix and

the wires and mesh. This was probably due to the high viscosity of the epoxy, which resulted in a mix of low density.

Test of Slab Made with Asbestos

45. Test 35 (See Plate 15b):

Reinforcing . . .	3% of chrysotile asbestos fibres, and 2x2 - 14/14 wire mesh at the center.
Concrete	Z = 0.50
Compressive Strength, psi	Unknown
Flexural Strength, psi	270
Maximum Fragment Velocity, fps	217
Fragmentation, % Intact	15

Failure was by shear at the supports, with the center reduced completely to small rubble. The failure of the mesh was by bond. Fragments were scattered to a distance of 275 feet.

46. Discussion: The maximum fragment velocity was 91% of that for the plain slabs. Although the compressive strength of the concrete was not known, it was probably less than 3,000 psi, based upon the flexural strength obtained. This would account for the complete disintegration of the slab into fragments ranging in size from sand-like particles to pieces weighing five pounds. Only the parts of the slab that were in bearing remained in large pieces. The low strength of the concrete was due to the excessive water that had to be added to keep the mix workable. Asbestos fibres absorb an extremely large amount of water during mixing. Because of this, the use of asbestos as random-fibre-reinforcement for this type of construction remains in question.

Tests of Slabs Made with Two-inch Polyurethane Foam Core

47. Tests 47 and 51 (See Plate 16):

Reinforcing . . .	2% of .017 x 1 1/2-inch steel wire, and 4x4 -8/8 wire mesh on each face.
Concrete	Mix A; Z = 0.50
Average Compressive Strength, psi	7180
Average Flexural Strength, psi	970
Maximum Fragment Velocity (Avg.), fps	240
Average Fragmentation, % Intact	57

Failure was by shear at the supports, with complete breakup of the center portion of the slab into rubble. The foam was compressed to 3/4 inch, and separated from the concrete. The wire mesh failed in tension. Fragments were scattered to a distance of 460 feet.

48. Tests 48 and 57 (See Plate 17):

Reinforcing . .	1 3/4% of 15 Denier x 3/4-inch nylon, and 4x4 - 8/8 wire mesh on each face.
Concrete	Mix A; Z = 0.50
Average Compressive Strength, psi	6255
Average Flexural Strength, psi	850
Maximum Fragment Velocity (Avg.), fps	259
Average Fragmentation, % Intact	45

Failure was primarily by shear at the supports, with some evidence of failure by flexure. The center of the slab broke into small pieces; the foam was compressed to 1/2-inch in places, and separated from the concrete. The wire mesh failed in both bond and tension. Fragments were scattered to a distance of 478 feet.

49. Discussion: Neither of the combinations of foam and nylon or foam and wire reduced fragmentation or fragment velocities under that of plain slabs. All of the center portions of the slabs were reduced to rubble, indicating very little resistance to the blast. The foam was compressed to 1/2 inch in the areas closest to the charge. Since this is within the "locking" range for the foam, it explains the poor response of the slabs.

Tests of Slabs Made with a Two-inch Core of Aluminum Honeycomb

50. Tests 44 and 53 (See Plate 18):

Reinforcing . . .	2% of .017 x 1 1/2-inch steel wire, and 4x4 -8/8 wire mesh on each face.
Concrete	Mix A; Z = 0.50
Average Compressive Strength, psi	6830
Average Flexural Strength, psi	1060
Maximum Fragment Velocity (Avg.), fps	213
Average Fragmentation, % Intact	55

Failure was by shear at the supports, and by flexure at the center. There was considerable breakup of the center portions of the slabs. The aluminum honeycomb was compressed to 1/4 inch at the point nearest the charge, and completely separated from the concrete (See Plate 19a). The wire mesh failed in bond and tension. Fragments were scattered to a distance of 410 feet.

51. Tests 49 and 50 (See Plate 20):

Reinforcing . . 1 3/4% of 15 Denier x 3/4-inch nylon and 4x4 - 8/8 wire mesh on each face.	
Concrete	Mix A; Z = 0.50
Average Compressive Strength, psi	5420
Average Flexural Strength, psi	765
Maximum Fragment Velocity (Avg.), fps	236
Average Fragmentation, % Intact	45

Failure was by shear at the supports, with complete breakup of the center portion of the slab. The aluminum honeycomb was compressed to 1/4 inch at the point nearest the charge, and the major portion was separated from the concrete. The wire mesh failed in tension and bond. Fragments were scattered to a distance of 440 feet.

52. Discussion: The slabs made with aluminum honeycomb and 15-Denier nylon did not reduce the fragmentation or fragment velocities under that of plain slabs. Those made with aluminum honeycomb and wire fibres reduced velocities 11%, and showed some resistance to breakup. However, the aluminum was compressed to 1/4 inch at the point nearest the charge, thus "locking" it and permitting full passage of the shock wave. It is apparent that two inches of shock-absorbing material is not sufficient for overpressures of this magnitude.

PHASE III TESTING

General

53. Sixteen slabs were tested as part of the Phase III program, as follows: four slabs reinforced with wire mesh; four slabs reinforced with wire mesh and 1 3/4% of 15-Denier nylon; four slabs reinforced with wire mesh and 1 3/4% of .017 x 1 1/2-inch wire; and four slabs reinforced with No. 3 reinforcing bars, two without fibres and one each with 1 3/4% of the 15-Denier nylon and the .017-inch wire. The objective of the tests on the slabs made with the wire mesh was to determine the normal scaled distance (Z) at which no fragments were produced by a 10-pound charge of Composition B. This was accomplished by varying the distance of the charge. All other test procedures remained the same as in previous tests. The objectives of the tests on the slabs made with reinforcing bars were: (1) to determine the effectiveness of tying reinforcing bar mats together as shown in Plate 27, and (2) to determine the effectiveness of fibrous reinforcing when used in conjunction with conventional reinforcing. The test procedures for these slabs followed those used in the Phase II testing.

54. The fibre percentage was reduced from 2 1/2% to 1 3/4% for the Phase III tests. This was a result of the analysis of the Phase II tests, which showed that there was no difference in the amount and velocity of the fragments for slabs containing 2 1/2% fibres from that of slabs containing 1 3/4% as tested in Phase I. In addition, moderate strength concrete, Mix B (4160 psi), was used for all of the Phase III tests. Results of Phase III tests are presented in Table 4, and analyzed in the following paragraphs.

Tests of Plain Concrete Slabs

55. Test 65 (See Plate 21a):

Reinforcing	4x4 - 8/8 wire mesh on each face
Concrete	Mix B; Z = 0.50 (13 in.)
Compressive Strength, psi	5345
Flexural Strength, psi	725
Maximum Fragment Velocity, fps	251
Fragmentation, % Intact	0

Failure was by shear at the supports, with complete breakup of the center portion of the slab. The concrete separated from the mesh, leaving it fairly intact. Concrete fragments were scattered to a distance of 380 feet.

56. Test 54 (See Plate 21b):

Reinforcing	4x4 - 8/8 wire mesh on each face
Concrete.	Mix B; Z = 1. 0 (26 in.)
Compressive Strength, psi	4121
Flexural Strength, psi	675
Maximum Fragment Velocity, fps	135
Fragmentation, % Intact	45

Failure was by flexure, and by shear at the supports. The mesh failed primarily in tension. Concrete fragments were scattered to a distance of 200 feet.

57. Test 58 (See Plate 22a):

Reinforcing	4x4 - 8/8 wire mesh on each face
Concrete.	Mix B; Z = 1. 5 (39 in.)
Compressive Strength, psi	3425
Flexural Strength, psi	605
Maximum Fragment Velocity, fps	87
Fragmentation, % Intact	63

Failure was primarily by flexure, with some shear failure at the supports. The wire mesh failed in tension. Small concrete fragments were scattered to a distance of 100 feet.

59. Test 59 (See Plate 22b):

Reinforcing	4x4 - 8/8 wire mesh on each face
Concrete	Mix B; Z = 2. 0 (52 in.)
Compressive Strength, psi	3855
Flexural Strength, psi	660
Maximum Fragment Velocity, fps	56
Fragmentation, % Intact	90

Failure was by flexure at the center portion of the slab. Relatively few fragments were produced, and these were probably due to the bending of the slab rather than from the overpressure or shock wave. The wire mesh failed in tension.

60. Discussion: These tests show clearly that the predominate mode of failure for this type of test is flexure. In Test 59, the normal scaled distance of the charge was 52 inches; yet the slab failed in flexure, producing some fragments. Close examination of the slab showed no evidence of severe damage, except at the point of flexure failure. This leads to the conclusion that the fragments were produced by the bending of the slab, as might be expected from any brittle material subjected to bending. It can then be stated that for Z = 2. 0, no fragments were produced.

Tests of Nylon-Reinforced Slabs

61. Test 66 (See Plate 23a):

Reinforcing	1 3/4% of 15-Denier nylon, and 4x4 - 8/8 wire mesh on each face
Concrete	Mix B; Z = 0. 50 (13 in.)
Compressive Strength, psi	4180
Flexural Strength, psi	705
Maximum Fragment Velocity, fps	228
Fragmentation, % Intact	42

Failure was by shear at the supports, with complete breakup of the center portion of the slab. The wire mesh failed in tension and bond. Concrete fragments were scattered to a distance of 339 feet.

62. Test 62 (See Plate 23b):

Reinforcing . . .	1 3/4% of 15-Denier nylon, and 4x4 - 8/8 wire mesh on each face
Concrete	Mix B; Z = 0. 75 (19. 5 in.)
Compressive Strength, psi	4120
Flexural Strength, psi	725
Maximum Fragment Velocity, fps	153
Fragmentation, % Intact	82

Failure was by flexure, and by shear at the supports. Only a small number of fragments were produced; these were scattered to a distance of 265 feet. The wire mesh failed in tension and bond; however, there was evidence that the mesh on the acceptor side of the slab did not have the full 3/4 inch of cover.

63. Test 61 (See Plate 24a):

Reinforcing . . .	1 3/4% of 15-Denier x 3/4-inch nylon, and 4x4 - 8/8 wire mesh
Concrete	Mix B; Z = 1. 0 (26 in.)
Compressive Strength, psi	3625
Flexural Strength, psi	655
Maximum Fragment Velocity, fps	125
Fragmentation, % Intact	80

Failure was by flexure and partially by shear at one of the supports. Very few fragments were produced; the major portion probably resulting from the bending of the slab. The wire mesh failed in tension.

64. Test 60 (See Plate 24b):

Reinforcing . . .	1 3/4% of 15 Denier x 3/4-inch nylon, and 4x4 - 8/8 wire mesh on each face
Concrete	Mix B; Z = 1.5 (39 in.)
Compressive Strength, psi	4500
Flexural Strength, psi	705
Maximum Fragment Velocity, fps	0
Fragmentation, % Intact	81

Failure was by flexure at the center of the slab, with the wire mesh failing in tension. No fragments were produced.

65. Discussion: These tests showed again that flexure was the principal mode of failure for this type of test. From the appearance of the slabs for Z = 0.75 or greater, it is doubtful if any fragments were produced that would be damaging. To assure no fragmentation, the charge distance required was 39 inches, or Z = 1.5.

Tests of Wire-Reinforced Slabs

66. Test 67 (See Plate 25a):

Reinforcing . . .	1 3/4% of .017 x 1 1/2-inch steel wire, and 4x4 - 8/8 wire mesh on each face
Concrete	Mix B; Z = 0.50 (13 in.)
Compressive Strength, psi.	6365
Flexural Strength, psi	825
Maximum Fragment Velocity, fps	211
Fragmentation, % Intact	55

Failure was by shear at the supports, with complete breakup of the slab. Concrete fragments were scattered to a distance of 355 feet. The wire mesh failed in tension.

67. Test 63 (See Plate 25b):

Reinforcing . . .	1 3/4% of .017 x 1 1/2-inch steel wire, and 4x4 - 8/8 wire mesh on each face
Concrete	Mix B; Z = 0.75 (19.5 in.)
Compressive Strength, psi	4155
Flexural Strength, psi	665
Maximum Fragment Velocity, fps.	136
Fragmentation, % Intact	61

Failure was by flexure and by shear at the supports. Only a small amount of fragments was produced. The wire mesh failed in tension.

68. Test 68 (See Plate 26a):

Reinforcing . . .	1 3/4% of .017 x 1 1/2-inch steel wire, and 4x4 - 8/8 wire mesh on each face
Concrete	Mix B; Z = 1.0 (26 in.)
Compressive Strength, psi	5755
Flexural Strength, psi	780
Maximum Fragment Velocity, fps	72
Fragmentation, % Intact	89

Failure was by flexure, with slight breakup of some of the slabs near the supports. The wire mesh failed in tension. Only a few fragments were formed.

69. Test 72 (See Plate 26b):

Reinforcing . . .	1 3/4% of .017 x 1 1/2-inch steel wire, and 4x4 - 8/8 wire mesh on each face
Concrete	Mix B; Z = 1.5 (39 in.)
Compressive Strength, psi	4560
Flexural Strength, psi	680
Maximum Fragment Velocity, fps	0
Fragmentation, % Intact	97

Failure was by flexure on one side of the center, with a large crack in the same relative position on the other side of the center. No fragments were produced. The wire mesh failed in tension.

70. Discussion: These tests show also that the principal mode of failure for this type of test is flexure. Although very few fragments were produced by the slabs with Z = 0.75 or greater, there was some breakup of the slabs. In order to produce no fragments, the required charge distance was 39 inches, or Z = 1.5.

Tests of Conventional Reinforced Slabs

71. Test 70 (See Plate 28a):

Reinforcing . . .	No. 3 bars, 4 inches on center, each way, each face
Concrete.	Mix B; Z = 0.50
Compressive Strength, psi	4400
Flexural Strength, psi	700
Maximum Fragment Velocity, fps	253
Fragmentation, % Intact	0

Failure was by complete disintegration of the concrete into pieces less than 5-pounds weight. The fragments were scattered to a distance of 310 feet. Despite the reinforcing bars, the response of the slab was similar to that of a plain slab. The bars did not act as a unit, and none of the concrete adhered to them.

72. Test 71 (See Plate 28b):

Reinforcing . . .	No. 3 bars, 4 inches on center each way, each face, with tie bars. (See Plate 27)
Concrete	Mix B; Z = 0.50
Compressive Strength, psi	4715
Flexural Strength, psi	655
Maximum Fragment Velocity, fps	253
Fragmentation, % Intact	0

Failure appeared to be by flexure, with complete disintegration of the concrete. Only a few pieces of concrete remained attached to the bars; however, in contrast to Test 70, the reinforcing acted as a unit because of the bars tying the two mats together. This did not reduce the number or velocity of the fragments; the reinforcing mat was hurled 100 feet, and concrete fragments were scattered to a distance of 200 feet.

73. Test 69 (See Plate 29a):

Reinforcing . . .	1 3/4% of .017 x 1 1/2-inch steel wire, and No. 3 bars, 4 inches on center, each way, each face, with tie bars
Concrete	Mix B; Z = 0.50
Compressive Strength, psi	4510
Flexural Strength, psi	705
Maximum Fragment Velocity, fps	208
Fragmentation, % Intact	82

The slab failed in flexure, but remained virtually in one piece. There were a few fragments produced, but it was difficult to determine whether they resulted primarily from the shock wave or were caused by the severe bending of the slab. There was some bond failure of the bars on the acceptor side of the slab, which was caused by insufficient concrete cover. Apparently, the reinforcing mat slipped during placing of the concrete, and instead of 7/16-inch cover, only 3/16-inch cover existed in one area. There was no indication that the reinforcing bars had yielded. The entire slab was hurled 66 feet.

74. Test 68 (See Plate 29b):

Reinforcing . . .	1 3/4% of 15-Denier x 3/4-inch nylon, and No. 3 bars, 4 inches on center, each way, each face with tie bars

Concrete	Mix B; Z = 0.50
Compressive Strength, psi	4130
Flexural Strength, psi	710
Maximum Fragment Velocity, fps	202
Fragmentation, % Intact	85

Failure was by flexure; however, the slab remained in one piece. Some fragments were produced, but as stated for Test 69, it was difficult to determine the actual cause of fragmentation. Based upon the combination of the amount and velocity of the fragments, and the degree of integrity after the test, the overall response of this slab was probably superior to any slab of the entire program.

75. Discussion: Two significicnt conclusions can be drawn from this series of tests: (1) that reinforcing bars alone do not reduce the amount or velocity of fragments, even though the bars can be made to respond as a unit; and (2) that concrete made with steel or nylon fibres, sufficiently reinforced to withstand the shear and flexure stresses, can effectively reduce the amount and velocity of fragments from concrete subjected to an explosive loading.

PART V: DISCUSSION OF RESULTS

76. The effectiveness of steel and synthetic fibres as random reinforcing for portland cement concrete has been determined in this program by comparing the response of fibrous-reinforced concrete to that of plain concrete. Fragment velocities, as measured by high-speed photography, and the degree of integrity of the slab after testing, based upon the weight of the larger pieces, were the two properties compared. The mixing properties of the fibres were considered in the final recommendation. The values for the plain slabs, which were used as the basis for comparison, were 240 fps as the maximum fragment velocity, and a zero degree of integrity; since the plain slabs produced no fragments larger than 5 pounds. These values are taken from Tests 37 and 46 of Phase II.

77. Upon completion of the Phase I testing, the question arose as to the difference in behavior under explosive loading of high- and moderate-strength concrete. Table 5 shows a comparison of concrete made from Mix A (having a basic compressive strength of approximately 6600 psi), with concrete made from Mix B (having a basic compressive strength of approximately 4300 psi). Comparing tests of plain concrete slabs reinforced with 4x4 - 8/8 wire mesh, it is seen that the fragment velocities from the slabs made with Mix A concrete are approximately 20% lower than the fragment velocities from the slabs made with Mix B. When the test slabs were made with nylon-monofilament or steel-wire fibres, the difference in fragment velocities between Mix A and Mix B concrete was reduced 7 - 8%. It appears that when concrete is to be reinforced with fibres, essentially equivalent response to explosive loading will be obtained with either Mix A or Mix B. It might be pointed out, however, that if the fibrous concrete is to be subjected to severe exposure conditions, it would be necessary to restrict the water-cement ratio to 0.53 by weight (maximum of 6 gallons per bag of cement) in order to produce a concrete leaving a compressive strength in the range of 5000 - 5500 psi.

78. Slabs reinforced with steel wires and wire mesh reduced fragment velocities 23%, and fragmentation by 70% or more. Slabs reinforced with wire produced the superior overall response of all the slabs containing wire mesh. As with the nylon and plain slabs, there was no significant difference in the response of slabs made with high- and medium-strength concrete. It is pointed out that the excessively high compressive and flexural strengths of the wire-reinforced concrete were due to the presence of the wires.

79. The slabs reinforced with fiberglas rods, in place of wire mesh, reduced fragment velocities 10 and 21% for the nylon- and steel-wire reinforced slabs respectively. Since these values are almost identical to the values obtained for the same type of slab with wire mesh, it is concluded that the fiberglas rods did not improve the response in any way. In addition, the degree of integrity (32 and 55%) was considerably less than that for the wire-mesh reinforced slabs. This ineffectiveness of the fiberglas rods was attributed to the poor bond developed between the rods and the concrete.

80. The concrete made with polypropylene and polyethylene fibres responded in a manner quite similar to the concrete made with nylon. The fragment velocities of the two polypropylene slabs averaged 223 fps, or 93% that of the plain slabs. The polyethylene slab produced a fragment velocity of 222 fps. This compared with the average for the nylon slabs, which was 218 fps. The average amount of slab that remained intact was in excess of 60% for the polypropylene, and 40% for the polyethylene; for the nylon it was 55%. The polypropylene is approximately one-third lower in cost than the nylon; and since the response appears to be equal, further investigation of this material is warranted.

81. The slab made with polypropylene fly screen reduced fragment velocities 26%, but the percentage of integrity was only 27%. The entire center portion was reduced to rubble. The test that combined both the fly screen and the 15-Denier nylon reduced the fragment velocity 16%, and maintained an integrity in excess of 56%. These results, though promising, do not overshadow the inherent difficulty of placing this type of material in concrete. Based upon the bond tests of the individual fibres from the screen (See Table 1 and Plate 30), it would seem that far-superior results could be obtained if the polypropylene could be crimped similar to the screen fibre, and supplied in short lengths for random use in the concrete. It can be seen from the bond tests that the crimped fibre developed sufficient bond to fail the fibre in tension, and was the only fibre for which this occurred.

82. The slab made of epoxy-resin-concrete produced a maximum fragment velocity of 103% of the plain slabs, and maintained an integrity of only 20%. This poor response is due directly to an inadequate mix design; therefore, this test should not be used to judge the effectiveness of epoxy concrete. The epoxy used was too viscous and as a result, a very low density concrete was produced. If further tests of this kind are conducted, a less viscous adhesive should be used. Polyester resins are an example of this type of adhesive and are considerably less expensive than epoxies.

82. The slab made with asbestos fibres produced a fragment velocity which was 90% of that of the plain slabs, but had an integrity of only 15%. But here again, this test cannot be used to judge the effectiveness of the asbestos; since the large amount of water, needed to keep the mix workable in order to overcome the absorption by the fibres, weakened the concrete. This was evidenced by the low flexural strength of 270 psi. A true evaluation can only be made if slabs are constructed using a very dry mix, such as is used in the concrete pipe industry.

83. The slabs made with the 2-inch core of polyurethane foam or aluminum honeycomb warrant very little discussion. It is quite obvious from all of the tests that two inches of either of these materials is not sufficient to withstand the high overpressures of this explosive test. Any reduction in the fragmentation and velocity was due to the presence of the nylon and steel-wire fibres. If further tests are conducted with these materials, an analytical study should be made to determine more precisely the necessary thickness required.

84. The tests to determine the normal scaled distance (Z) for which no fragments would be produced gave the following results:

a. For Plain Slabs. The distance required was 52 inches (Z = 2.0). Some fragments were produced at this range, but since the maximum velocity was only 56 fps, it is doubtful if any damage would result from them. Examination of the slab leads to the conclusion that the fragments are a result of the bending of the slab, rather than from the high overpressures.

b. For the Nylon- and Wire-Reinforced Slabs. The distance required was 39 inches (Z = 1.5). For all of these tests, in which Z = 0.75 or more, the primary mode of failure was flexure. Since a certain amount of fragments are undoubtedly caused by flexural break, it becomes difficult to determine the actual distance at which no fragments would be produced by the blast. However, the distance given here would be a maximum, and would thus be on the safe side.

85. The tests conducted on the slabs made with the No. 3 reinforcing bars best demonstrated the effectiveness of the fibres in producing a shock-resistant concrete. The reinforcing was designed to resist the large shear and flexure stresses that caused failure of the slabs made with wire mesh, and made fibre evaluation so difficult. The tests proved that reinforcing bars used alone reduce neither the fragmentation nor velocity. For the two tests of slabs without fibres, but with reinforcing bars, the maximum fragment velocity was 253 fps for both tests, and the entire slabs were reduced to rubble. For the fibrous-reinforced concrete, the velocities were only approximately 80% of the non-fibrous slabs, and the amount of fragmentation was less than 18% of the total weight of the slabs; these fragments appeared to be more a result of the bending of the slabs, rather than from the overpressures or shock wave. The fact that none of the reinforcing bars yielded in the fibrous concrete slabs indicates that they were over-reinforced for these pressures. Therefore, less reinforcement should be used in subsequent tests.

PART VI: CONCLUSIONS

86. Based on the data presented herein, the following conclusions are believed warranted:

a. Concrete made with randomly distributed synthetic or steel-wire fibres can effectively resist the overpressures and shock waves from high explosives, provided sufficient conventional reinforcing is used to prevent breakup due to the shear and flexural stresses.

b. With properly designed fibrous concrete, fragment velocities can be reduced 20%, and the number of fragments can be reduced in excess of 80%.

c. The fibres which produced the best results and which were the least difficult to mix were the 15-Denier x 3/4-inch nylon and the .017 x 1 1/2-inch steel wire.

d. The failure mode is primarily flexure for a slab in a vertical position with bearing only on two sides. This causes considerable breakup of the slab and evaluation of the fibres is difficult, since there is no way to distinguish between the mechanisms causing failure.

e. Only a slight difference in response to explosive loading should be expected between basic high- and moderate-strength concretes when they are fibrous-reinforced.

PART VII: RECOMMENDATIONS

87. To further develop fibrous concrete for resisting explosive forces, the following recommendations are made:

a. That the 15-Denier nylon fibres and the .017 x 1 1/2-inch steel wire be tested full-scale.

b. That producers of fibres be encouraged to increase the bond characteristics of the various materials.

c. That deformed steel wire and synthetic fibres be obtained for static bond tests and for explosive tests with 10-pound charges.

d. That consideration be given to increasing the size of charge to 30 pounds for slab testing, with appropriate increases in slab properties and Z distances.

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3. Ohio River Division Laboratories, Fibrous Reinforcement for Portland Cement Concrete, Tech. Report 2-40, U. S. Army Engineer Division, Ohio River, Cincinnati, Ohio, May 1965.

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Table 1

Results of Bond Tests of Fibres

Type and Size of Fibre	Final Loads, psi	Remarks
.017-inch Steel Wire	711, 818, 852, 374 295, 374 Ave. = 570	Wires failed in bond
.010-inch Steel Wire	265, 415, 390, 535 490 Ave. = 420	Wires failed in bond
.010-inch Nylon Monofilament	10, 25, 30, 20, 20, 15 Ave. = 20	Fibres failed in bond
.014-inch Crimped Polypropylene	160, 135, 145, 140, 160 Ave. = 148	Fibres failed in tension

Conditions of Tests: 3/8-inch aggregate
1-inch embedment
Type III cement
Rate of Strain = 0.2 in./min.

Table 2

Dividing Wall Program - Phase I Test Results

Test No.	Conventional Reinforcement		Fibrous Reinforcement			Concrete		Concrete Strength, psi		Charge wt., lbs.	Factor	Fragment Velocity, fps	% Slab Intact	Remarks
	Type	Size	%	Type	Size	Mix Type	Age, Days	Compressive	Flexural					
2	--	--	--	--	--	A	13	7180	915	10	0.50	240	--	Slab disintegrated
3	--	--	--	--	--	A	13	6290	787	10	0.50	220	--	Slab disintegrated
22	--	--	--	--	--	A	78	7415	930	10	0.50	*	--	Slab disintegrated
23	--	--	--	--	--	A	78	5730	800	10	0.50	240	--	Slab disintegrated
13	--	--	1 3/4	Nylon	15 Denier x 3/4 inch	A	14	4513	523	10	0.50	*	--	Slab disintegrated
18	--	--	1 3/4	Nylon	0.010 x 3 inch	A	10	3820	583	10	0.50	271	50	--
14	--	--	1 3/4	Steel Wire	0.017 x 1 1/2 inch	A	14	4445	802	10	0.50	*	--	Slab disintegrated
19	--	--	1	Steel Wire	0.032 x 3	A	10	3573	635	10	0.50	257	--	Slab disintegrated
1	Wire Mesh	4 x 4 - 8/8	--	--	--	A	14	6810	847	10	0.50	198	--	Slab disintegrated
4	Wire Mesh	4 x 4 - 8/8	--	--	--	A	14	6490	785	10	0.50	196	--	Slab disintegrated
6	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon	15 Denier x 3/4 inch	A	9	6035	782	10	0.50	189	--	Slab disintegrated
7	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon	15 Denier x 3/4 inch	A	9	5660	770	10	0.50	187	--	Slab disintegrated
10	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon	15 Denier x 3/4 inch	A	16	5213	595	10	0.50	*	40	--
16	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon	0.010 x 3 inch	A	16	4908	755	10	0.50	168	75	--
17	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon	0.010 x 3 inch	A	16	5382	770	10	0.50	213	50	--
24	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon	0.010 x 3 inch	A	43	8006	940	10	0.50	*	40	--
5	Wire Mesh	4 x 4 - 8/8	1	Steel Wire	0.010 x 1 inch	A	142	--	1107	10	0.50	172	--	Slab disintegrated
8	Wire Mesh	4 x 4 - 8/8	1 3/4	Steel Wire	0.017 x 1 1/2 inch	A	16	7770	1090	10	0.50	162	70	--
9	Wire Mesh	4 x 4 - 8/8	1 3/4	Steel Wire	0.017 x 1 1/2 inch	A	16	7640	1102	10	0.50	180	60	--
15	Wire Mesh	4 x 4 - 8/8	1 3/4	Steel Wire	0.017 x 1 1/2 inch	A	40	7562	1017	2 1/2	0.33	216	80	--
11	Wire Mesh	4 x 4 - 8/8	1	Steel Wire	0.032 x 3 inch	A	10	4383	666	10	0.50	*	60	--
12	Wire Mesh	4 x 4 - 8/8	1	Steel Wire	0.032 x 3 inch	A	10	5833	849	10	0.50	*	60	--
20	Wire Mesh	4 x 4 - 8/8	1	Steel Wire	0.032 x 3 inch	A	17	4497	705	10	0.50	189	50	--
21	Wire Mesh	4 x 4 - 8/8	3	Asbestos	KB - 483 - 4T	A	219	--	583	10	0.50	*	--	Slab disintegrated

* Camera malfunction, no record of velocity

Table 3

Dividing Wall Program - Phase II Test Results

Test No.	Conventional Reinforcement Type	Conventional Reinforcement Size	%	Fibrous Reinforcement Type	Fibrous Reinforcement Size	Concrete Mix Type	Concrete Age, Days	Concrete Strength, psi Compressive	Concrete Strength, psi Flexural	Charge wt., lbs.	Z Factor	Fragment Velocity, fps	% Slab Intact*	Distance to Farthest Fragment	Remarks
37	--	--	--	--	--	A	14	6770	835	10	0.50	240	0	345'	---
46	--	--	--	--	--	A	15	6875	885	10	0.50	240	0	369'	---
33	Wire Mesh	4 x 4 - 8/8	--	--	--	B	20	3795	625	10	0.50	264	7	350'	---
34	Wire Mesh	4 x 4 - 8/8	--	--	--	B	20	3640	625	10	0.50	225	11	340'	---
25	Wire Mesh	4 x 4 - 8/8	2 1/2	Nylon	0.010 x 3-inch	A	32	5275	805	10	0.50	217	68	345'	---
32	Wire Mesh	4 x 4 - 8/8	2 1/2	Nylon	0.010 x 3-inch	A	47	5895	880	10	0.50	216	67	230'	---
39	Wire Mesh	4 x 4 - 8/8	2 1/2	Nylon	0.010 x 3-inch	A	61	6100	835	10	0.50	222	46	330'	---
30	Wire Mesh	4 x 4 - 8/8	2 1/2	Nylon	0.010 x 3-inch	B	13	3550	690	10	0.50	253	65	200'	---
40	Wire Mesh	4 x 4 - 8/8	2 1/2	Nylon	0.010 x 3-inch	B	27	3920	658	10	0.50	228	45	294'	---
26	Wire Mesh	4 x 4 - 8/8	2 1/2	Steel Wire	0.017 x 1 1/2-inch	A	33	8210	1075	10	0.50	177	77	264'	---
31	Wire Mesh	4 x 4 - 8/8	2 1/2	Steel Wire	0.017 x 1 1/2-inch	A	48	8525	1310	10	0.50	190	70	340'	---
41	Wire Mesh	4 x 4 - 8/8	2 1/2	Steel Wire	0.017 x 1 1/2-inch	A	62	8300	1335	10	0.50	240	77	360'	---
38	Wire Mesh	4 x 4 - 8/8	2 1/2	Steel Wire	0.017 x 1 1/2-inch	B	19	5505	960	10	0.50	247	64	440'	---
45	Wire Mesh	4 x 4 - 8/8	2 1/2	Steel Wire	0.017 x 1 1/2-inch	B	20	6475	918	10	0.50	188	80	282'	---
52	Wire Mesh	4 x 4 - 8/8	--	Galv. Wire Screen (1)	--	A	21	6570	770	10	0.50	280	7	280'	---
43	Fiberglas-Polyester resin bars	(2)	2	Steel Wire	0.017 x 1 1/2-inch	A	10	6900	1220	10	0.50	190	55	335'	---
42	Fiberglas-Polyester resin bars	(2)	1 3/4	Nylon	15 Denier x 3/4-inch	A	13	6035	921	10	0.50	215	33	415'	---
55	Wire Mesh	4 x 4 - 8/8	1	Nylon (3)	15 Denier x 3/4-inch	A	40	6260	885	10	0.50	202	56	276'	---
56	Wire Mesh	4 x 4 - 8/8	--	Polypropylene Fly Screen (4)	--	A	40	6010	805	10	0.50	177	28	415'	---
27	Wire Mesh	4 x 4 - 8/8	2 1/2	Polypropylene	0.0075 x 1-inch	A	29	5215	865	10	0.50	235	65	390'	---
28	Wire Mesh	4 x 4 - 8/8	2 1/2	Polypropylene	0.0065 x 1-inch	A	29	5360	780	10	0.50	211	61	330'	---
29	Wire Mesh	4 x 4 - 8/8	2 1/2	Polypropylene	0.011 x 1-inch	A	29	5315	755	10	0.50	222	44	340'	---
36	Wire Mesh	4 x 4 - 8/8	1	Steel Wire	0.010 x 1-inch	Epoxy	16	2680	990	10	0.50	247	20	365'	Epoxy Concrete Slab
35	Wire Mesh	2 x 2 - 14/14	3	Asbestos Fibre	--	-	262	--	270	10	0.50	217	14	275'	Type KB-483-4T Asb.
47	Wire Mesh	4 x 4 - 8/8	2	Steel Wire (5)	0.017 x 1 1/2-inch	A	13	7020	940	10	0.50	207	55	461'	Shock Absorb. Mat'l.
51	Wire Mesh	4 x 4 - 8/8	2	Steel Wire (5)	0.017 x 1 1/2-inch	A	28	7340	1003	10	0.50	272	50	435'	Shock Absorb. Mat'l.
48	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon (5)	15 Denier x 3/4-inch	A	8	4815	805	10	0.50	253	40	439'	Shock Absorb. Mat'l.
57	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon (5)	15 Denier x 3/4-inch	A	46	6040	805	10	0.50	234	51	478'	Shock Absorb. Mat'l.
44	Wire Mesh	4 x 4 - 8/8	2	Steel Wire (6)	0.017 x 1 1/2-inch	A	10	6585	1020	10	0.50	223	35	409'	Shock Absorb. Mat'l.
53	Wire Mesh	4 x 4 - 8/8	2	Steel Wire (6)	0.017 x 1 1/2-inch	A	25	7575	1100	10	0.50	203	62	360'	Shock Absorb. Mat'l.
49	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon (6)	15 Denier x 3/4-inch	A	8	4815	805	10	0.50	253	40	439	Shock Absorb. Mat'l.
50	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon (6)	15 Denier x 3/4-inch	A	11	6025	723	10	0.50	220	37	---	Shock Absorb. Mat'l.

* Pieces 20 lbs. or larger.

(1) 7 Layers

(2) 1/4-inch (4-inch C-C, each way, each face)

(3) Plus 5 Layers Polypropylene Fly Screen

(4) 5 Layers

(5) Plus 2-inch Polyurethane Foam

(6) Plus 2-inch Aluminum Honeycomb

Table 4

Dividing Wall Program - Phase III Test Results

Test No.	Conventional Reinforcement		Fibrous Reinforcement			Concrete		Concrete Strength, psi		Charge wt., lbs.	Z Factor	Fragment Velocity, fps	% Slab Intact*	Distance to Farthest Fragment	Purpose of Tests
	Type	Size	%	Type	Size	Mix Type	Age, Days	Compressive	Flexural						
65	Wire Mesh	4 x 4 - 8/8	--	--	--	B	24	5345	725	10	0.50	251	0	380'	Effects of Z Tests
54	Wire Mesh	4 x 4 - 8/8	--	--	--	B	24	4120	675	10	1.00	135	45	200'	Effects of Z Tests
58	Wire Mesh	4 x 4 - 8/8	--	--	--	B	24	3425	605	10	1.50	87	63	100'	Effects of Z Tests
59	Wire Mesh	4 x 4 - 8/8	--	--	--	B	24	3855	660	10	2.00	56	90	0	Effects of Z Tests
66	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon	15 Denier x 3/4-inch	B	29	4180	705	10	0.50	228	32	339'	Effects of Z Tests
62	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon	15 Denier x 3/4-inch	B	16	4210	725	10	0.75	153	82	264'	Effects of Z Tests
61	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon	15 Denier x 3/4-inch	B	16	3625	655	10	1.00	125	81	0	Effects of Z Tests
60	Wire Mesh	4 x 4 - 8/8	1 3/4	Nylon	15 Denier x 3/4-inch	B	11	4500	705	10	1.50	0	98	0	Effects of Z Tests
67	Wire Mesh	4 x 4 - 8/8	1 3/4	Steel Wire	.017 x 1 1/2-inch	B	27	6365	825	10	0.50	211	55	355'	Effects of Z Tests
63	Wire Mesh	4 x 4 - 8/8	1 3/4	Steel Wire	.017 x 1 1/2-inch	B	11	4155	665	10	0.75	136	61	0	Effects of Z Tests
64	Wire Mesh	4 x 4 - 8/8	1 3/4	Steel Wire	.017 x 1 1/2-inch	B	14	5755	780	10	1.00	72	88	0	Effects of Z Tests
72	Wire Mesh	4 x 4 - 8/8	1 3/4	Steel Wire	.017 x 1 1/2-inch	B	27	4560	680	10	1.50	0	97	0	Effects of Z Tests
70	#3 Bars	4-inch C-C, each face	--	--	--	B	8	4400	700	10	0.50	253	0	310'	Effects of Reinforcement
71	#3 Bars	4-inch C-C, each face**	--	--	--	B	8	4715	655	10	0.50	253	0	200'	Effects of Reinforcement
68	#3 Bars	4-inch C-C, each face**	1 3/4	Nylon	15 Denier x 3/4-inch	B	7	4130	710	10	0.50	202	89	Slab-85'	Effects of Reinforcement
69	#3 Bars	4-inch C-C, each face**	1 3/4	Steel Wire	.017 x 1 1/2-inch	B	8	4510	705	10	0.50	208	90	Slab-66'	Effects of Reinforcement

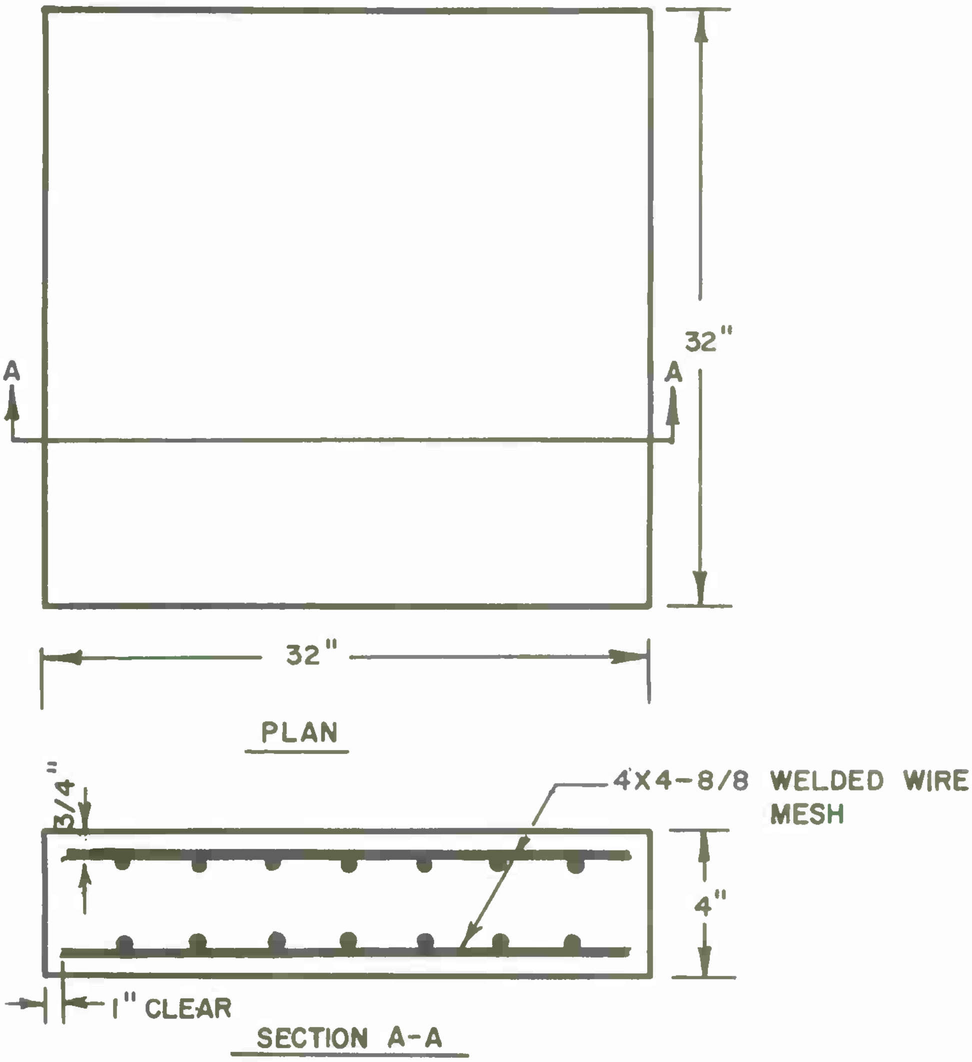
* Pieces 20 lbs. or larger

** Tie bars one direction

Table 5

Dividing Wall Program - Comparison of Mix A and Mix B Concrete

Test No.	Type Mix	Concrete Strength, psi		Fragment Velocity, fps	% Intact	Max. Distance ft.
		Compressive	Flexural			
		4 x 4 - 8/8 Wire Mesh Only				
1	A	6810	847	198	--	---
4	A	6490	785	196	--	---
Avg.		6650	816	197	--	---
33	B	3795	625	264	7	350
34	B	3640	625	225	11	340
65	B	5345	725	251	0	380
Avg.		4260	658	247	6	357
		4 x 4 - 8/8 Wire Mesh + 2 1/2% .010-inch x 3-inch Nylon				
25	A	5275	805	217	68	345
32	A	5895	880	216	67	230
39	A	6100	835	222	46	330
Avg.		5757	840	218	60	302
30	B	3550	690	253	65	200
40	B	3920	658	228	45	294
Avg.		3735	674	240	55	247
		4 x 4 - 8/8 Wire Mesh + 2 1/2% of .017-inch x 1 1/2-inch Steel Wire				
26	A	8210	1075	177	68	264
31	A	8525	1310	190	70	340
41	A	8300	1335	240	77	360
Avg.		8345	1240	202	72	321
38	B	5505	960	247	46	440
45	B	6475	918	188	80	282
Avg.		5990	939	217	63	361



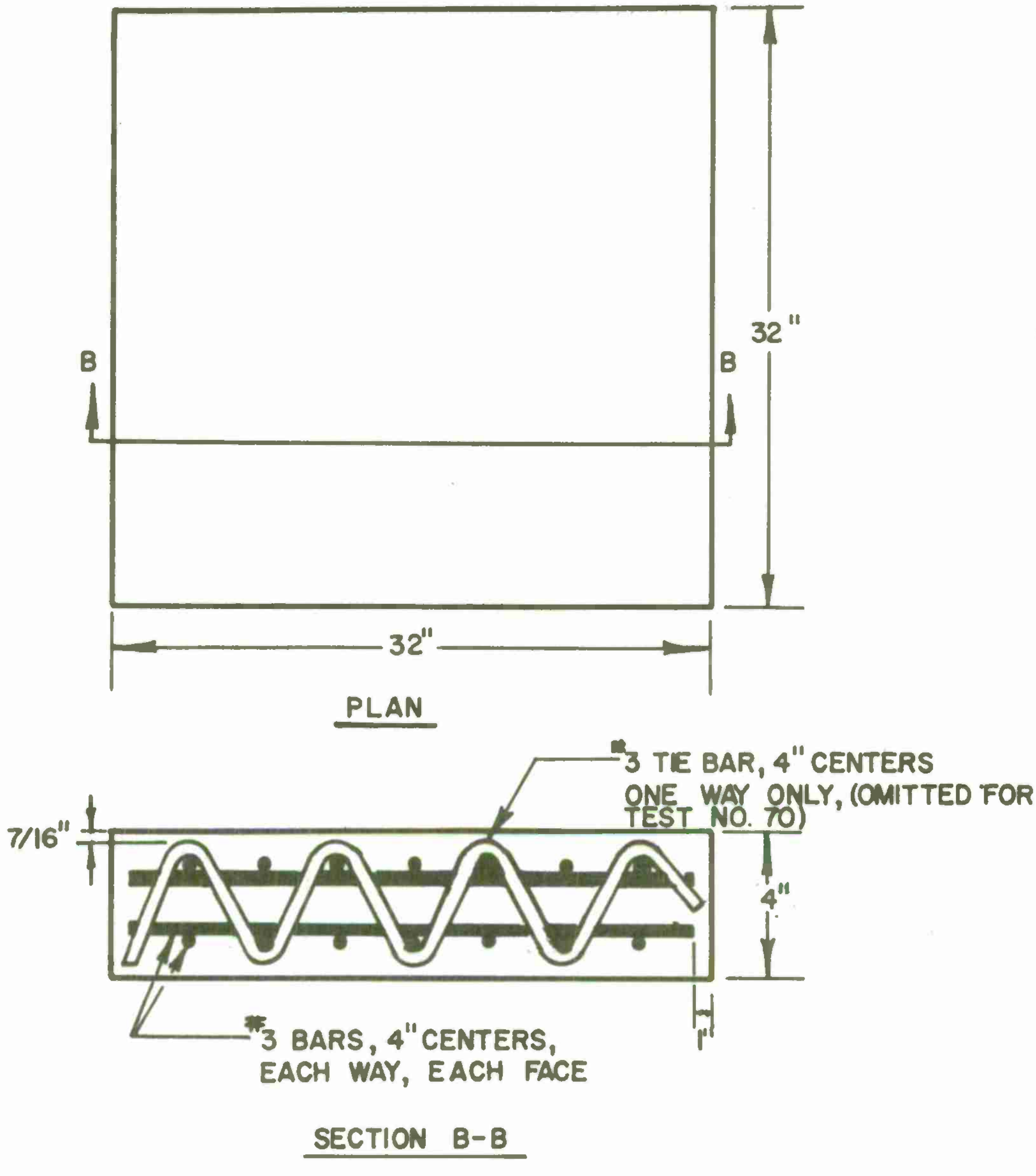
PLAN AND SECTION OF WIRE MESH-REINFORCED SLAB

RESPONSE OF FIBROUS-REINFORCED CONCRETE TO EXPLOSIVE LOADINGS

ORD LABORATORIES
CINCINNATI, OHIO

JANUARY 1966

FIGURE 1



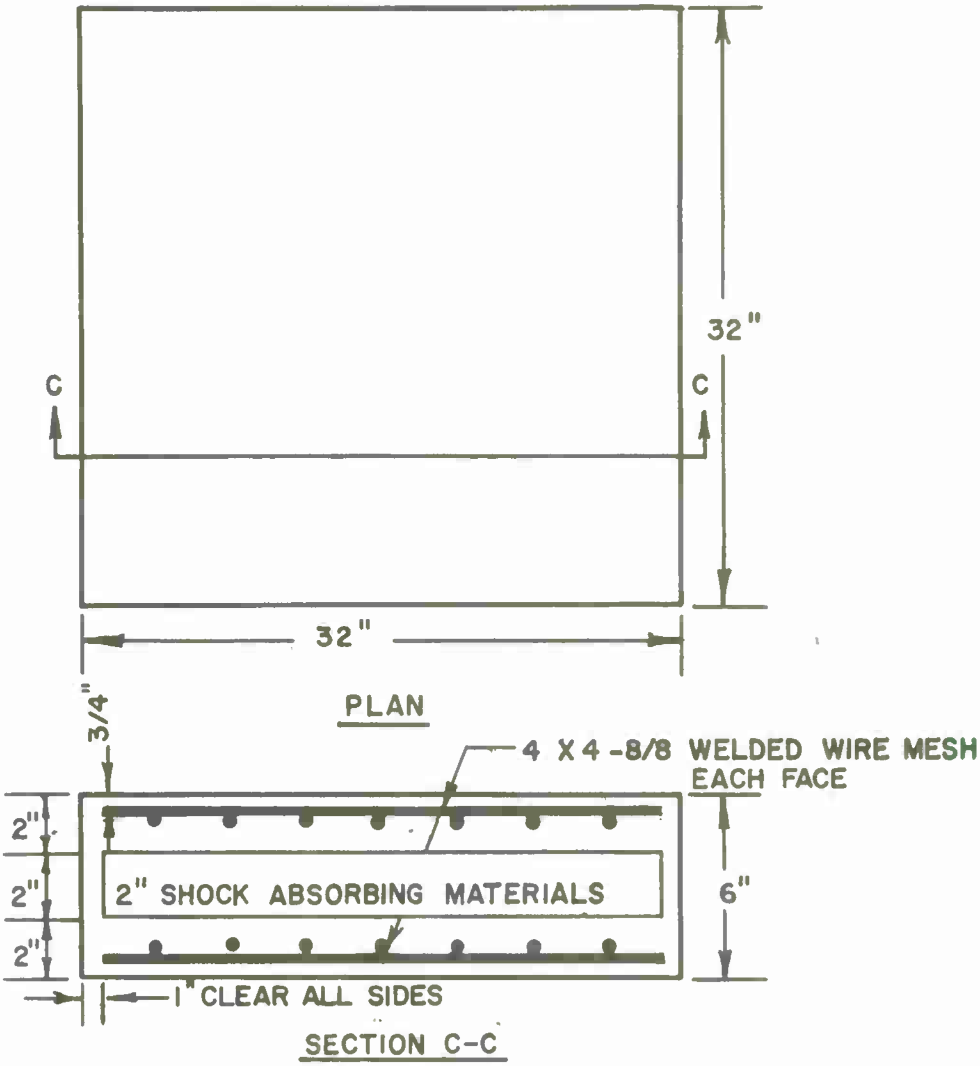
PLAN AND SECTION OF
BAR REINFORCED SLAB

RESPONSE OF FIBROUS-REINFORCED CONCRETE
TO EXPLOSIVE LOADINGS

ORD LABORATORIES
CINCINNATI, OHIO

JANUARY 1966

FIGURE 2



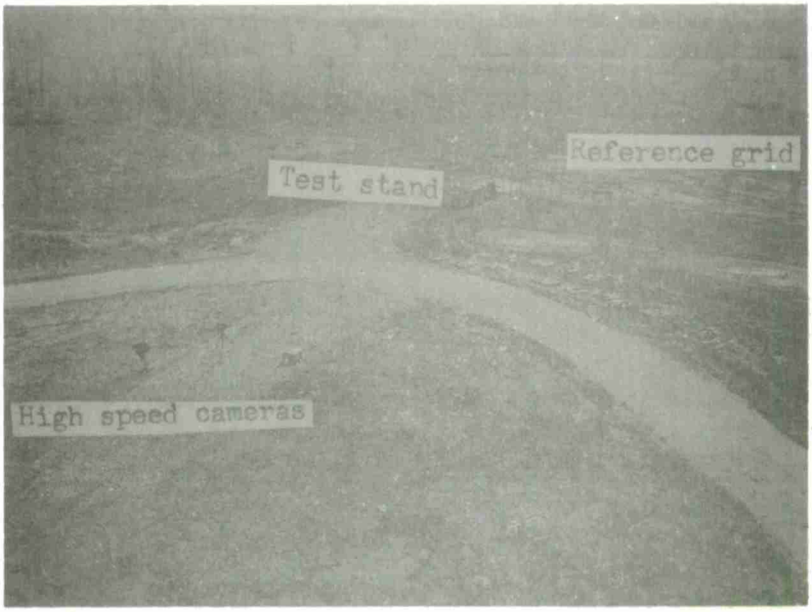
PLAN AND SECTION OF SLAB
INCORPORATING SHOCK-ABSORBING MATERIAL

RESPONSE OF FIBROUS-REINFORCED CONCRETE
TO EXPLOSIVE LOADINGS

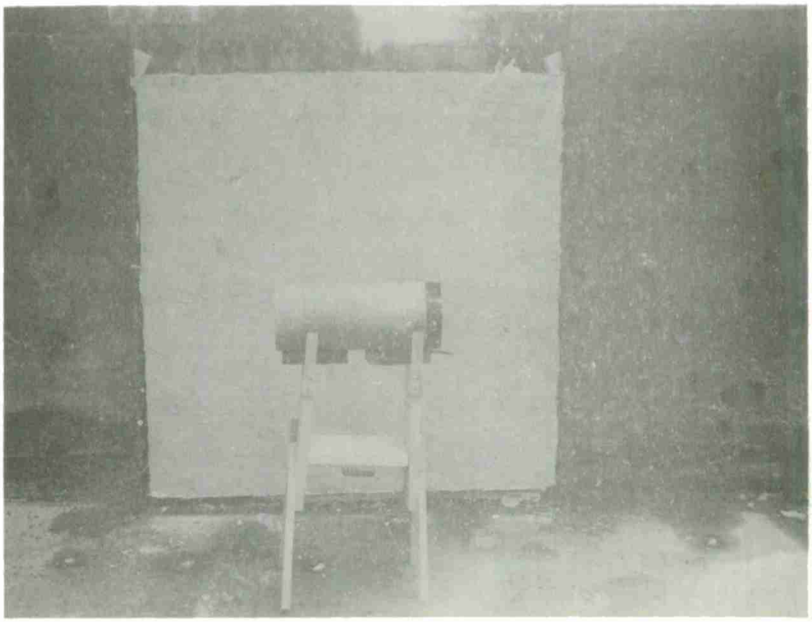
ORD LABORATORIES
CINCINNATI, OHIO

JANUARY 1966

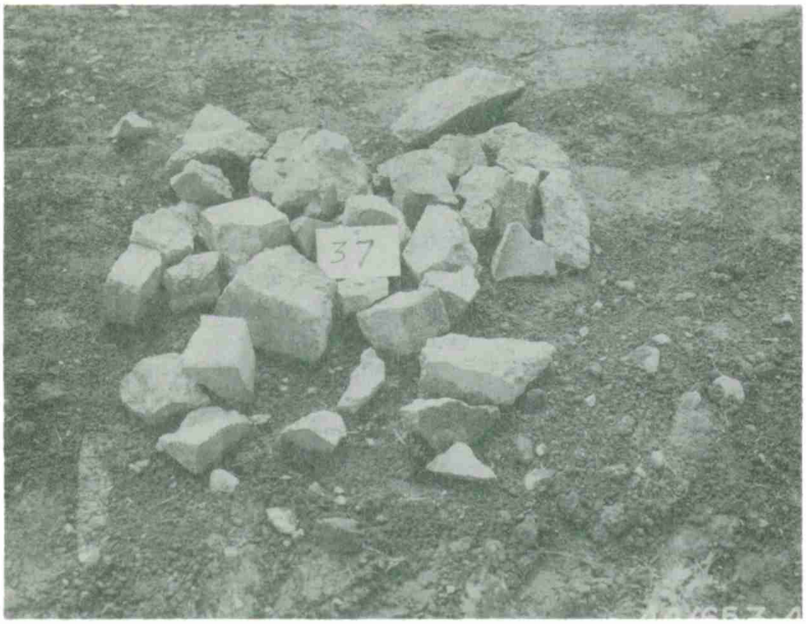
FIGURE 3



a. Test Range Where Explosive Tests were Conducted

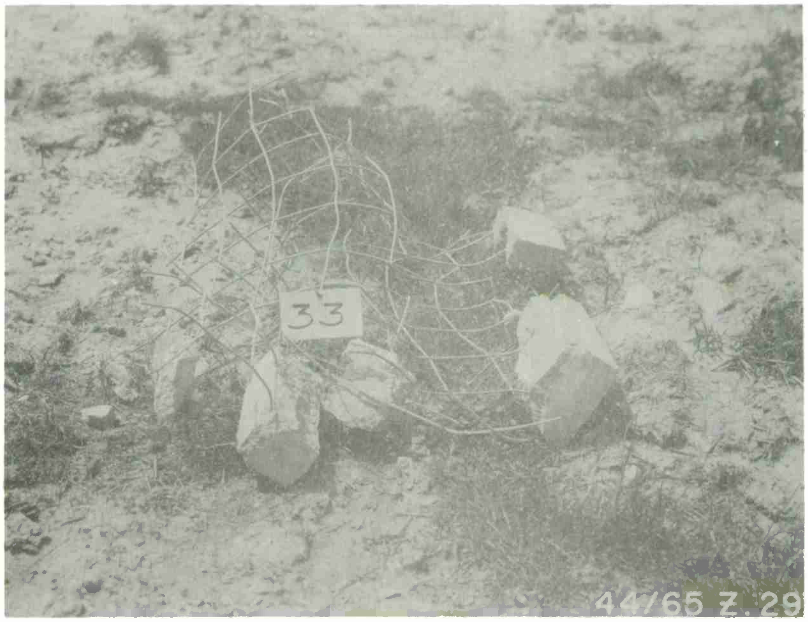


b. Test Slab in Position for Testing with a 10-lb. Charge of Composition B

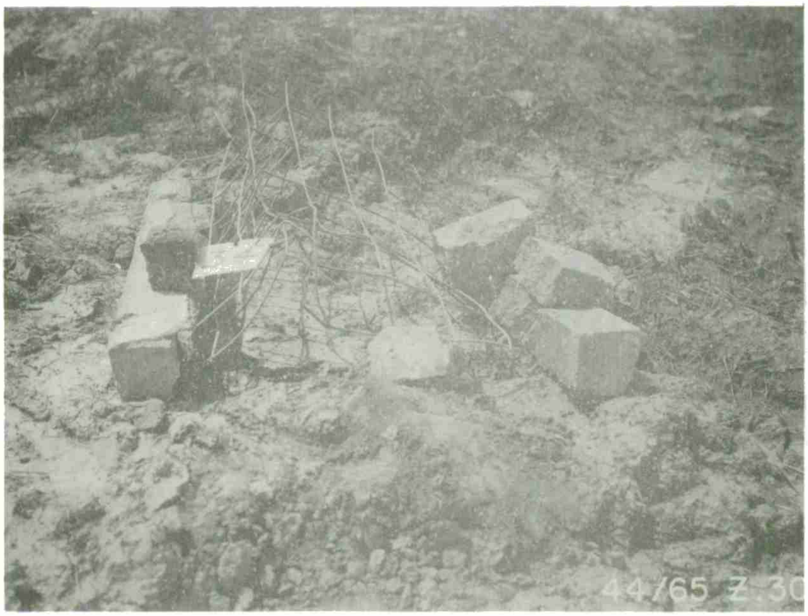


a. Post Shot View of Test 37;
20% of Slab Shown

b. Post Shot View of Test 46;
20% of Slab Shown

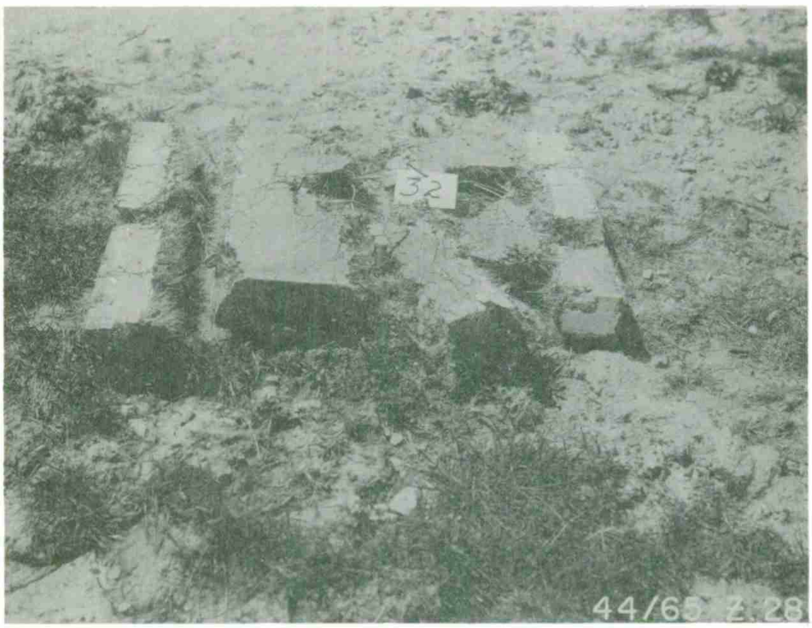


a. Post Shot View of Test 33;
14% of Slab Shown



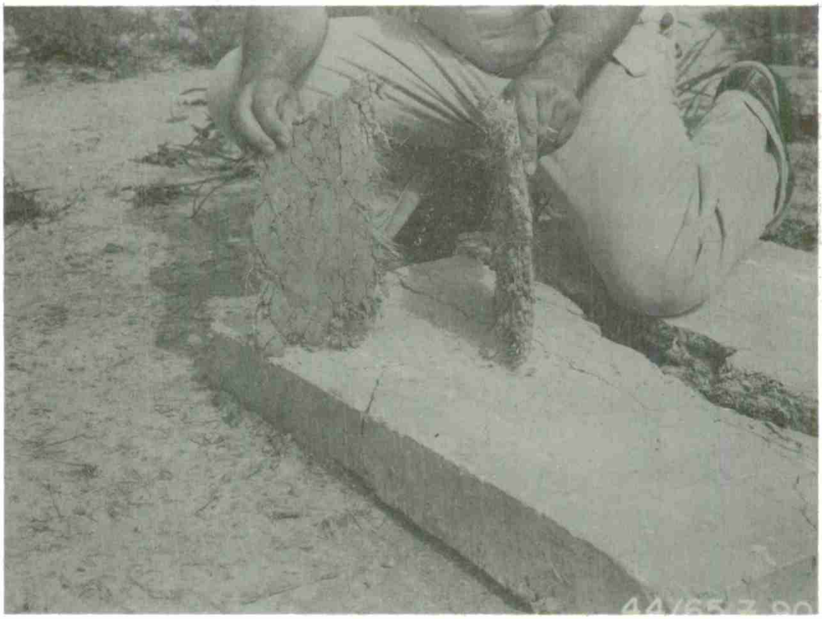
b. Post Shot View of Test 14;
21% of Slab Shown

a. Post Shot View of Test 25;
69% of Slab Shown



b. Post Shot View of Test 32;
77% of Slab Shown

PLATE 4

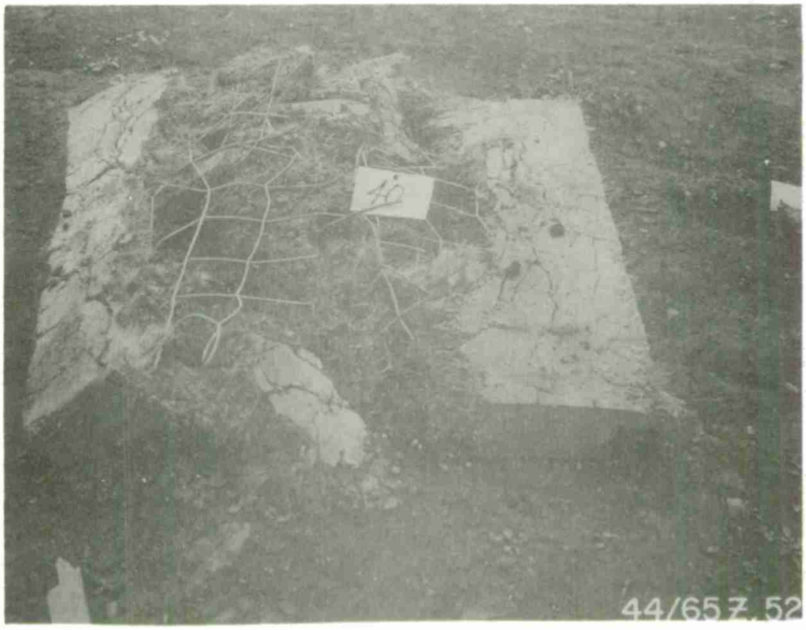


Spalled Concrete from a Nylon-
Reinforced Slab

PLATE 5

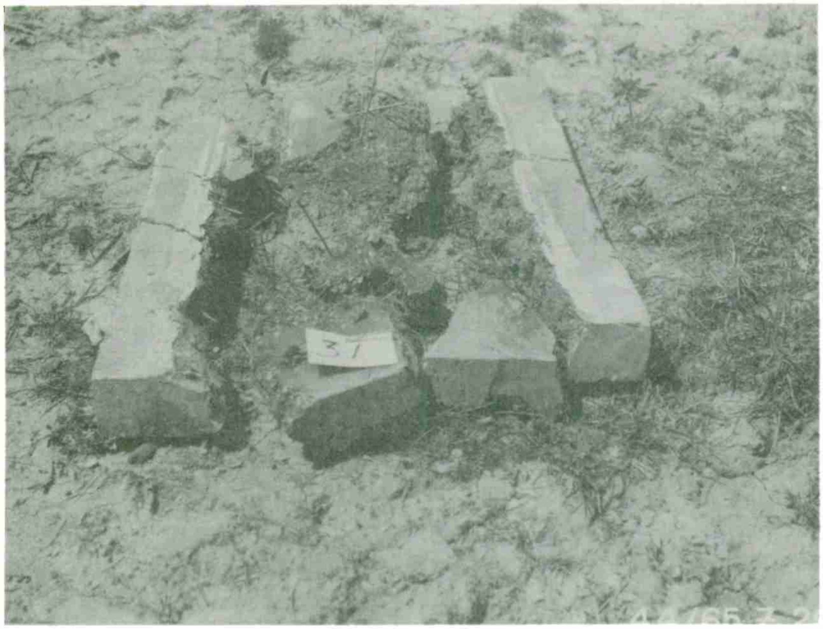
a. Post Shot View of Test 39;
60% of Slab Shown

b. Post Shot View of Test 30;
65% of Slab Shown



a. Post Shot View of Test 40;
67% of Slab Shown

b. Post Shot View of Test 26;
76% of Slab Shown

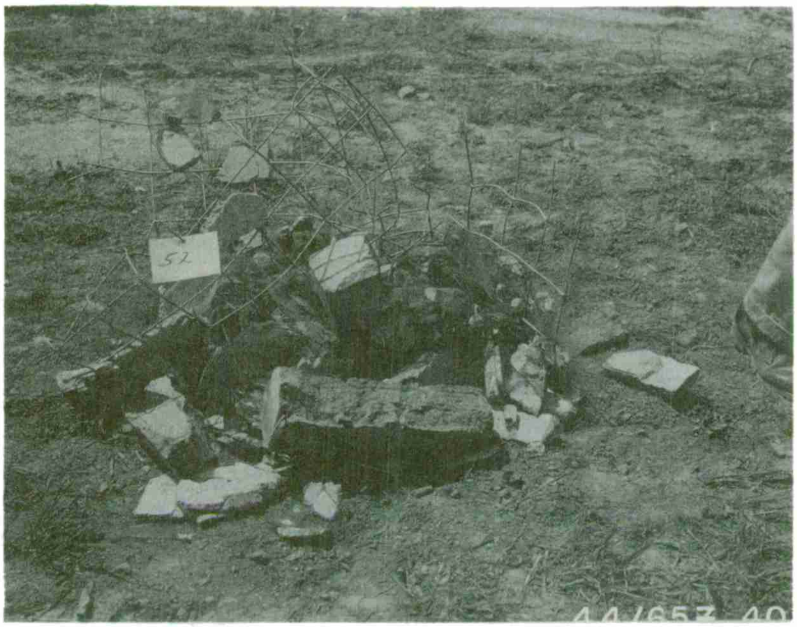


a. Post Shot View of Test 31;
73% of Slab Shown

b. Post Shot View of Test 41;
78% of Slab Shown

a. Post Shot View of Test 38;
69% of Slab Shown

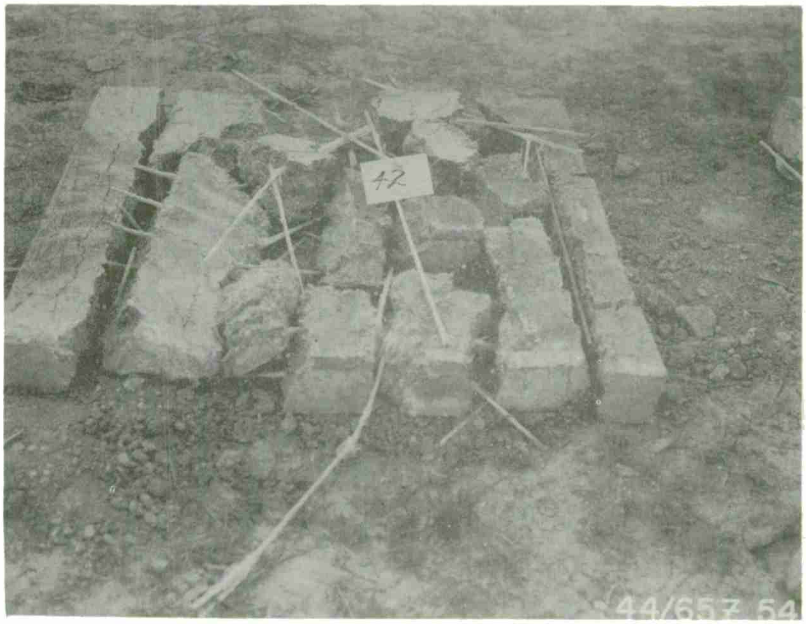
b. Post Shot View of Test 45;
83% of Slab Shown



Post Shot View of Test 52;
20% of Slab Shown

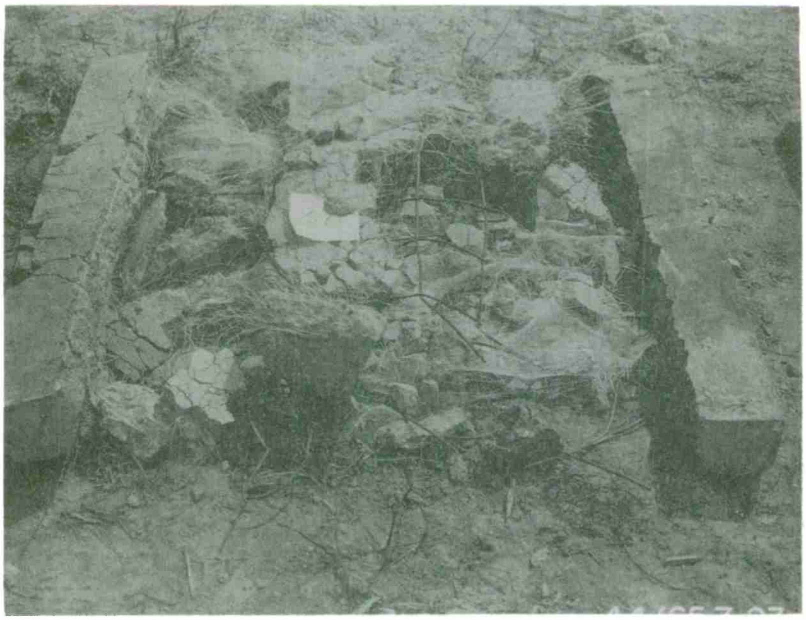
PLATE 10

a. Post Shot View of Test 43;
67% of Slab Shown



b. Post Shot View of Test 42;
75% of Slab Shown

a. Post Shot View of Test 55;
66% of Slab Shown



b. Post Shot View of Test 56;
40% of Slab Shown

RESPONSE OF FIBROUS REINFORCED
CONCRETE TO EXPLOSIVE LOADINGS

a. Post Shot View of Test 27;
71% of Slab Shown

b. Post Shot View of Test 28;
67% of Slab Shown

Post Shot View of Test 29;
49% of Slab Shown

PLATE 14

a. Post Shot View of Test 36;
50% of Slab Shown

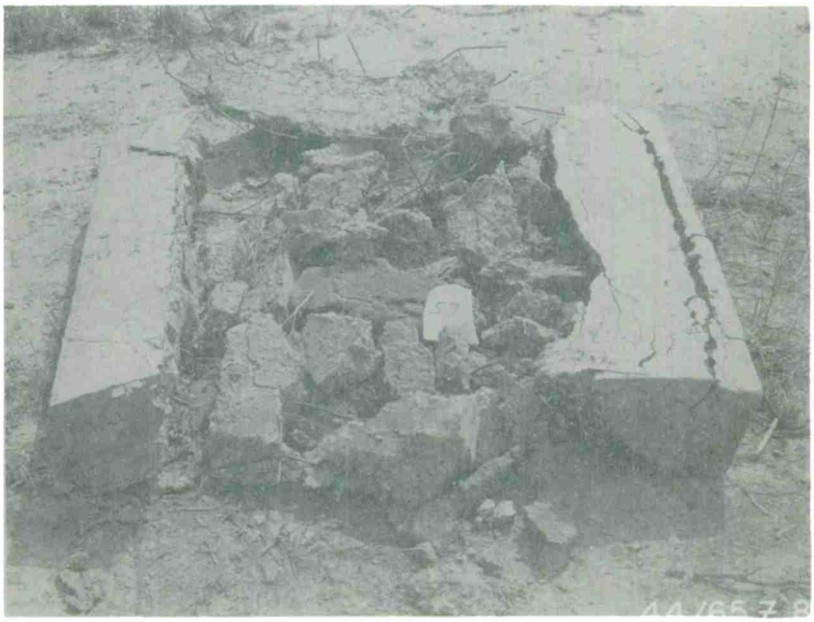
b. Post Shot View of Test 35;
27% of Slab Shown

a. Post Shot View of Test 47;
65% of Slab Shown

b. Post Shot View of Test 51;
54% of Slab Shown

RESPONSE OF FIBROUS REINFORCED
CONCRETE TO EXPLOSIVE LOADINGS

a. Post Shot View of Test 48;
64% of Slab Shown

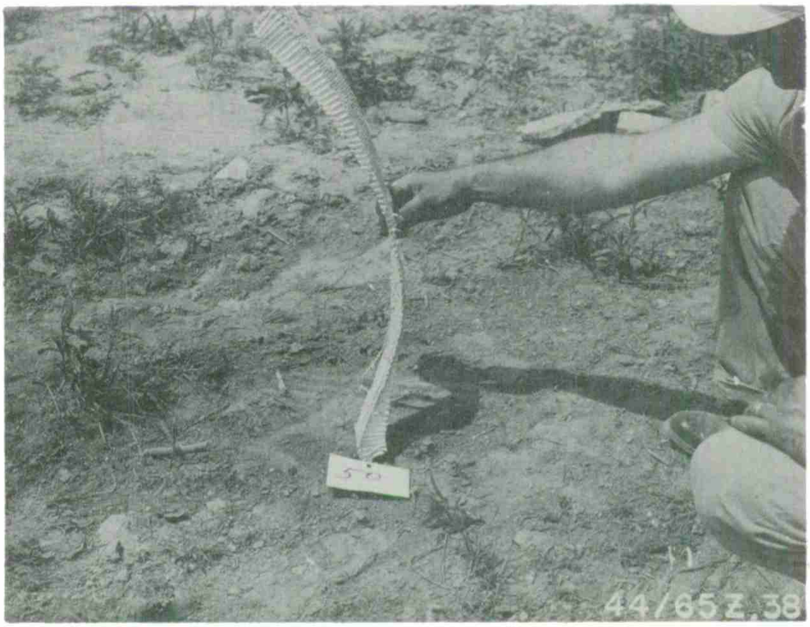


b. Post Shot View of Test 57;
50% of Slab Shown

RESPONSE OF FIBROUS REINFORCED
CONCRETE TO EXPLOSIVE LOADINGS

a. Post Shot View of Test 44;
64% of Slab Shown

b. Post Shot View of Test 53;
68% of Slab Shown

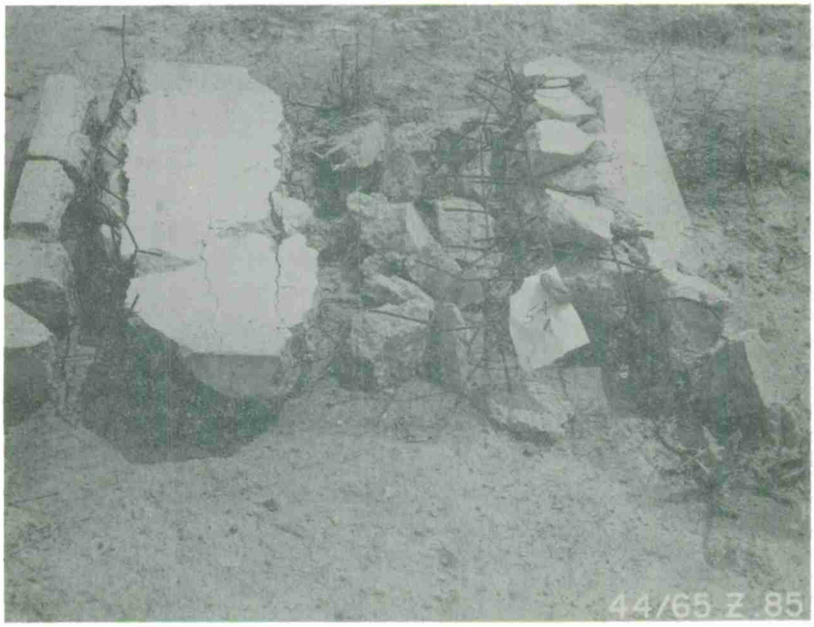


View of 2-inch Honeycomb
Compressed to 1/4 inch
By Blast

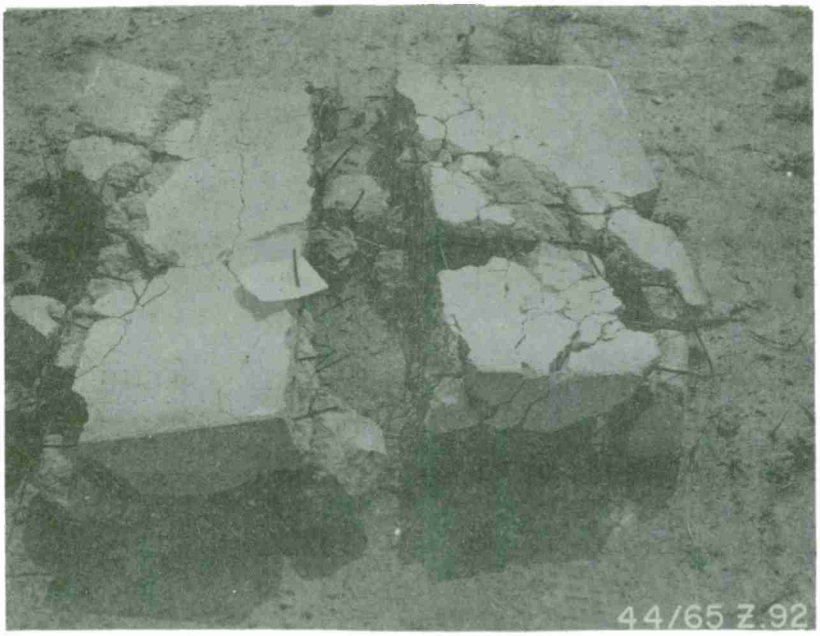
a. Post Shot View of Test 49;
63% of Slab Shown

b. Post Shot View of Test 50;
85% of Slab Shown

a. Post Shot View of Test 65;
23% of Slab Shown



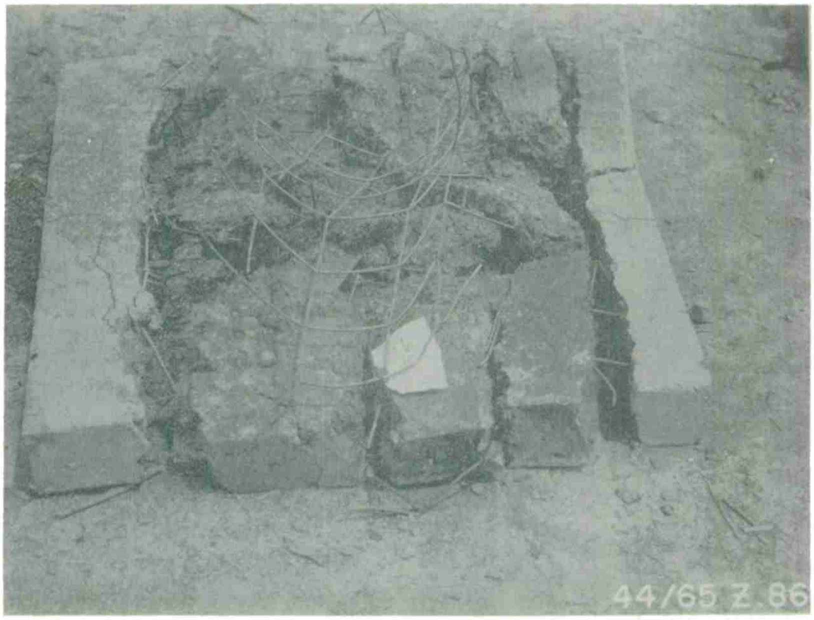
b. Post Shot View of Test 54;
60% of Slab Shown



a. Post Shot View of Test 58;
63% of Slab Shown

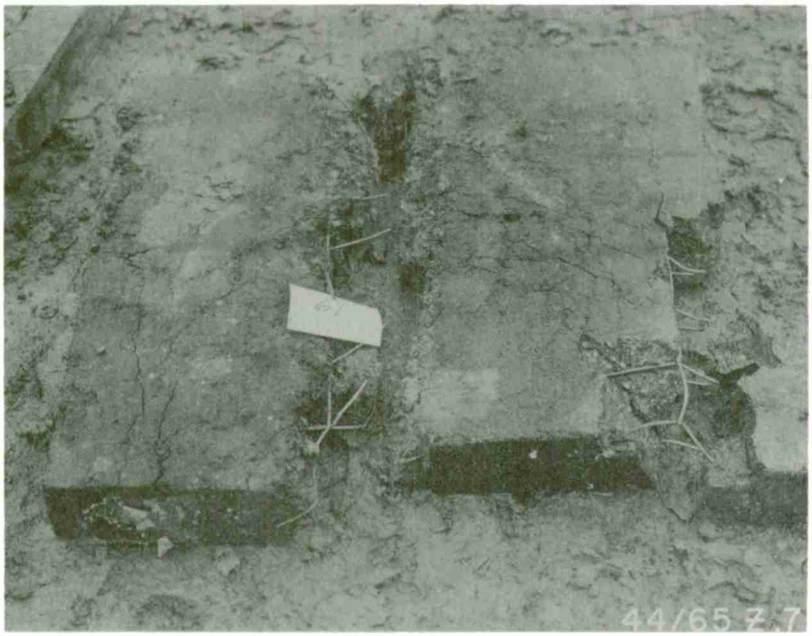
b. Post Shot View of Test 59;
91% of Slab Shown

RESPONSE OF FIBROUS FEINFORCED
CONCRETE TO EXPLOSIVE LOADINGS

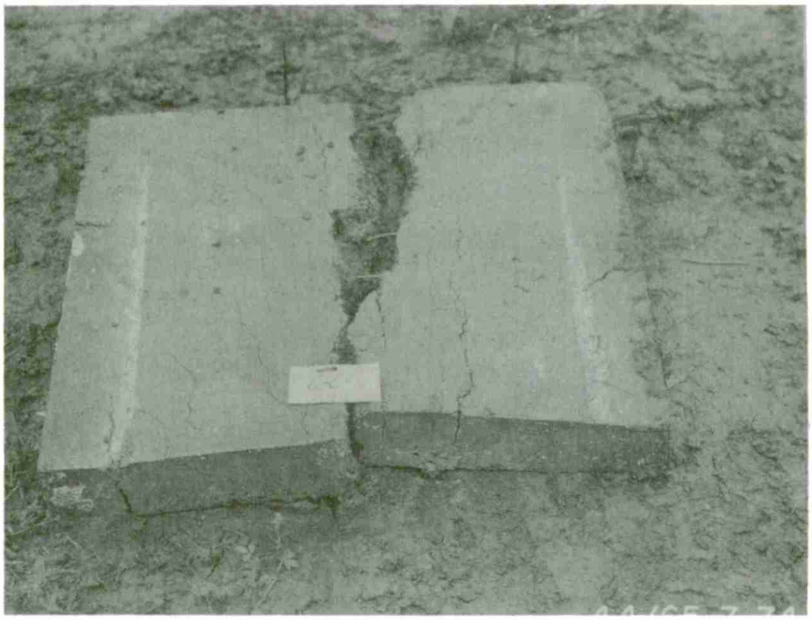


a. Post Shot View of Test 66;
65% of Slab Shown

b. Post Shot View of Test 62;
82% of Slab Shown



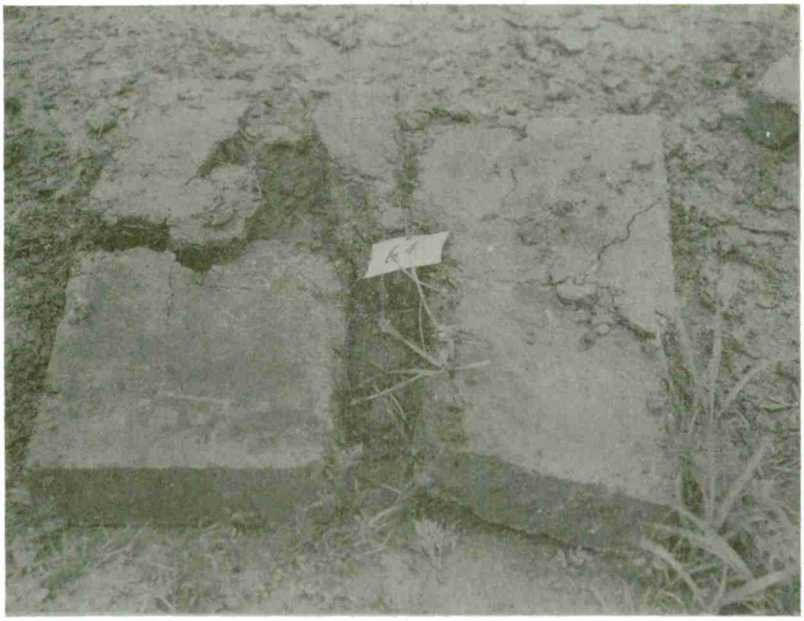
a. Post Shot View of Test 61;
80% of Slab Shown



b. Post Shot View of Test 60;
98% of Slab Shown

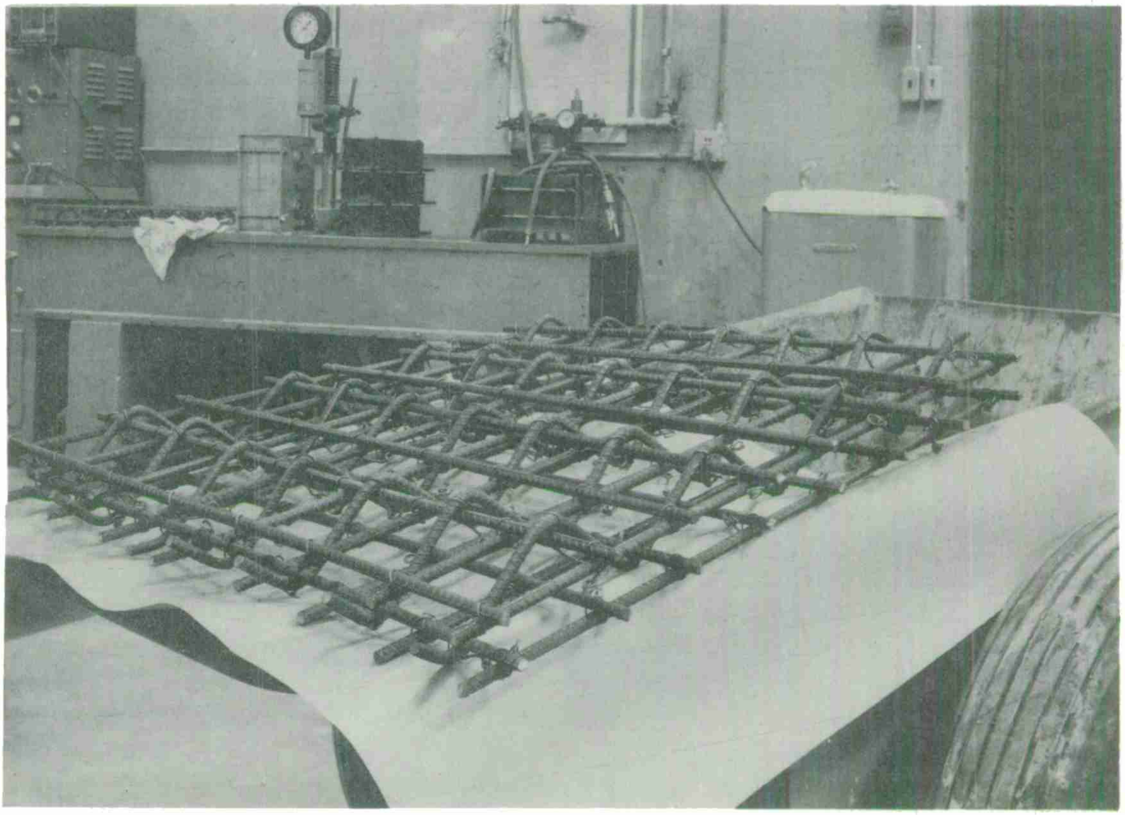
a. Post Shot View of Test 67;
72% of Slab Shown

b. Post Shot View of Test 63;
73% of Slab Shown



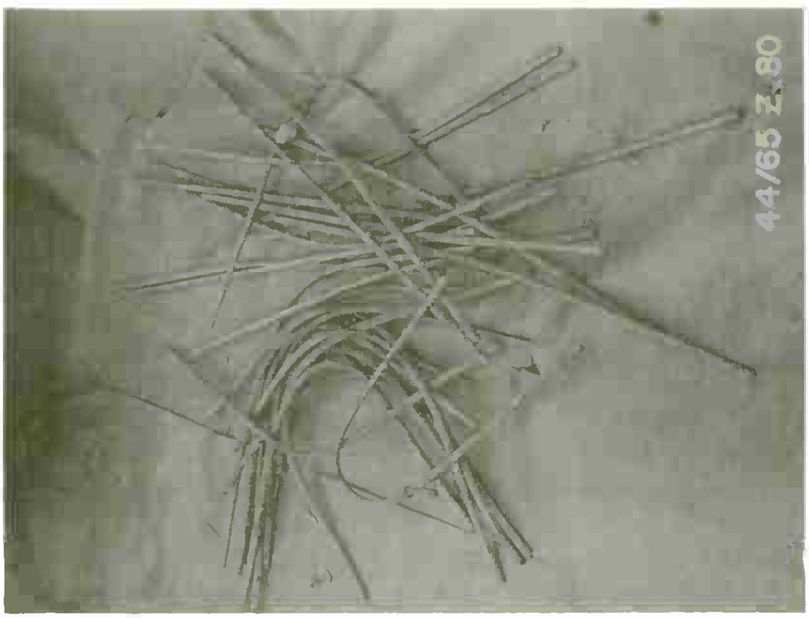
a. Post Shot View of Test 64;
89% of Slab Shown

b. Post Shot View of Test 72;
97% of Slab Shown



View of No. 3 Reinforcing Used to Resist the Shear and Flexural Stresses. Note the Bar Tying the Two Mats Together. This method of Reinforcing was Developed by Picatinny Arsenal. The Amount of Reinforcing in the Long. Direction is 1.97%;in the Transverse Direction, it is 1.33%

RESPONSE OF FIBROUS REINFORCED
CONCRETE TO EXPLOSIVE LOADINGS

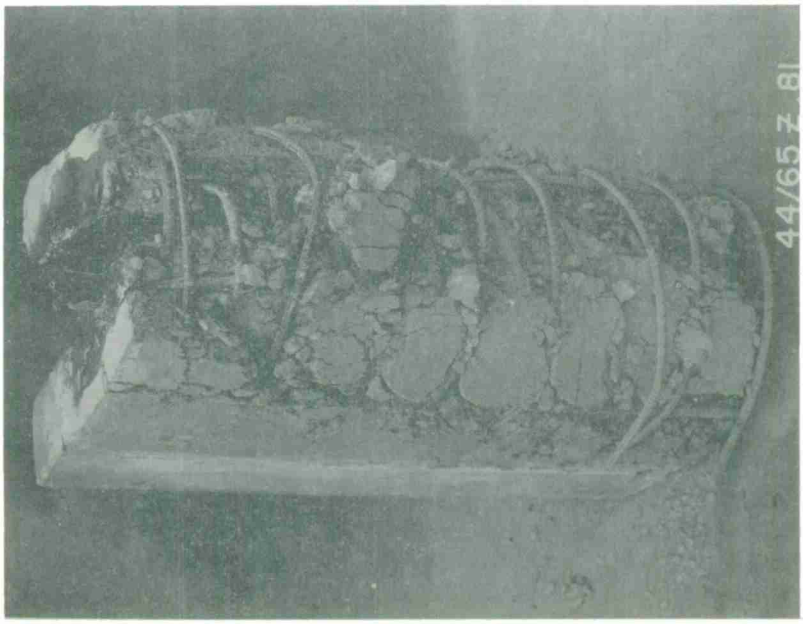


a. Post Shot View of Test 70;
Slab is Missing

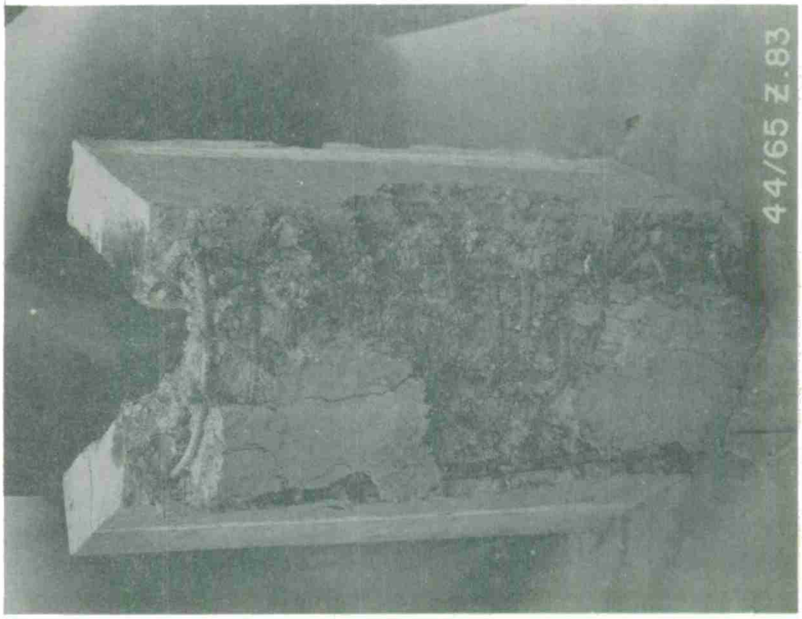
b. Post Shot View of Test 71;
Slab is Missing

PLATE 28

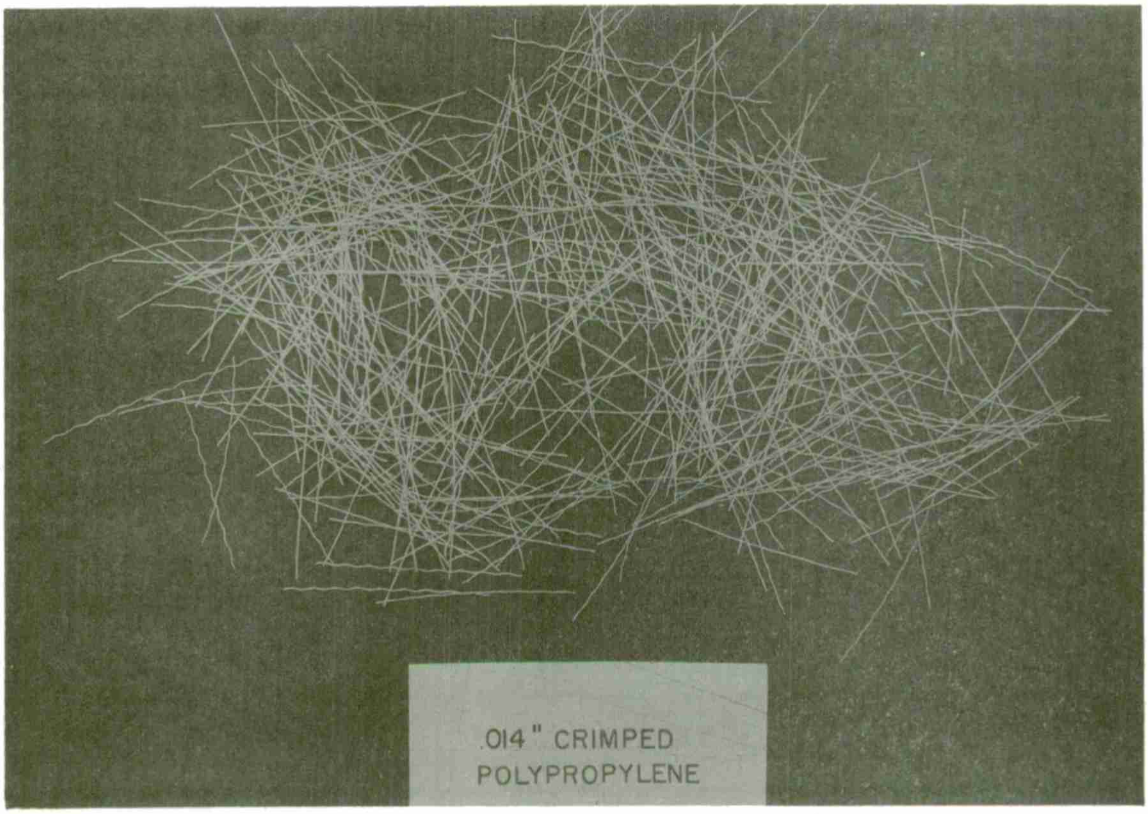
RESPONSE OF FIBROUS REINFORCED
CONCRETE TO EXPLOSIVE LOADINGS



a. Post Shot View of Test 69;
82% of Slab Shown



b. Post Shot View of Test 68;
85% of Slab Shown



Fibres Taken From Polypropylene Screen.
Note the Crimped Form

PLATE 30

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13. ABSTRACT

The results of 72 explosive loading tests on fibrous-reinforced concrete slabs are presented. The slabs, 32x32x4 inches, were tested in a vertical position with 4 inches of bearing on the two vertical sides. A 10-pound cylindrical charge of Composition B high explosive was used as the loading mechanism. Various synthetic and steel fibres were used as random reinforcing to develop a concrete that would resist explosive loadings. Evaluation was based upon the ability of the fibrous concrete to reduce the amount and velocity of fragments produced by the explosive loading. The values obtained from tests of plain, unreinforced concrete slabs were used as the basis of comparison. It is shown that when plain concrete slabs are reinforced conventionally to resist the shear and flexural stresses, there is no reduction in fragment velocities or fragmentation; and, that similarly reinforced slabs of fibrous concrete show 20% reduction in velocities, and over 80% reduction in fragmentation. A study made to evaluate high-strength and medium-strength concrete, when used in conjunction with fibres, revealed no significant difference in response under the explosive loading. The mode of failure for a slab supported on two sides only is shown to be primarily flexural. Detailed descriptions of each individual test are presented, together with conclusions and recommendations for future work.

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14. KEY WORDS	LINK A		LINK B		LINK C	
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